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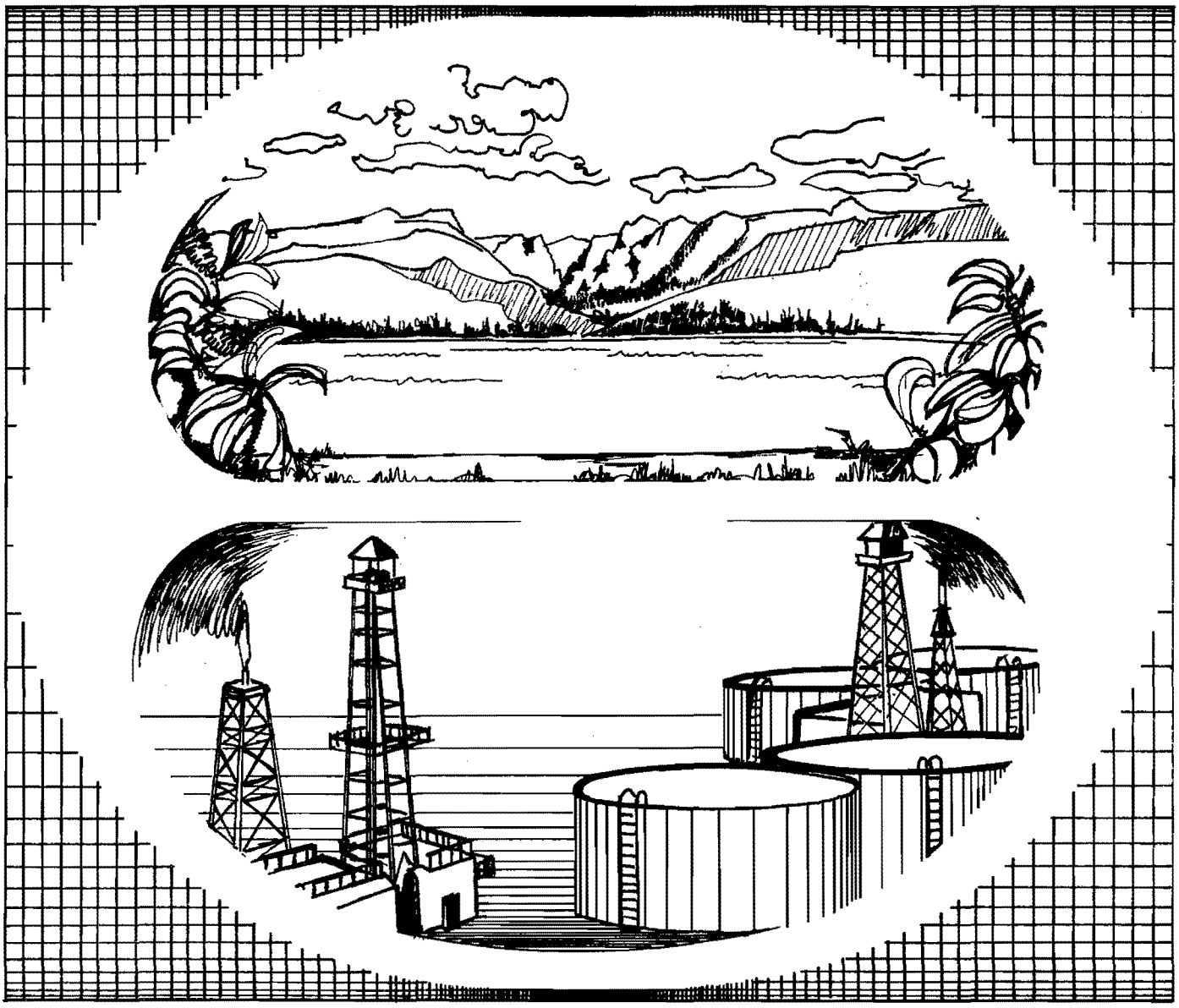

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by

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ABSTRACT

Responses of two freshwater lake ecosystems of the Intermountain West to crude oil impaction were investigated. The research was conducted in two phases; in the first phase effects of crude oil were studied on an ecosystem established in three phase laboratory microcosms (gaseous-aqueous-sediment), which simulated the natural lakes. Notable responses of the microcosm ecosystem to oil impaction included: an increased oxygen demand by the biological community, nutrient immobilization, a reduction in plant biomass accumulation and a heterotrophically dominated ecosystem. The increased availability of biologically degradable reduced carbon (i.e., the oil) and nutrient immobilization, rather than toxic effects of oil on plants, were the primary factors leading to a long-term imbalance between autotrophs and heterotrophs following oil addition.

The second phase of the research was designed to investigate effects of crude oil on plant litter decomposition in the same two lakes. In general, crude oil reduced the rate and extent of *in situ* litter decomposition, but activity of oiled-litter associated decomposer communities was greater than, or equal to, that of unoiled-litter over a year's period. Differences in the degree of crude oils' impacts between litter types and lakes were explained by factors such as biochemical structure of the plants, sediment types of the lakes and physical energy (e.g. wind) to the lakes. Increased rates of oxygen utilization because of the crude oil were identified as a potential primary detrimental effect of oil pollution. Crude oil did not affect the nutrient content of plant litter at any given stage of litter decomposition, but the rate of nutrient loss from the litter was reduced because of a reduction in the rate of litter decomposition. Of the nitrogen and phosphorus lost from plant litter, much less was released to ambient water in inorganic form from oiled litter than from unoiled litter. Nitrogen limitation to decomposers may have been the primary factor reducing the rate of oiled litter decomposition. Environmental ramifications of oil pollution concerning litter-environment nutrient exchange are discussed.

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INTRODUCTION

There has been considerable research performed on the impact of oil pollution due to shipping accidents, oil well blowouts, and pipeline failures on marine ecosystems. In contrast, little is known concerning the effects of oil on freshwater systems. Marine oil spills have involved massive accidents which affect large areas and attract worldwide media attention, whereas spills into freshwater systems are generally of smaller magnitude and more local in effect. Although a freshwater oil spill may be lesser in magnitude, its impact on the local environment might be more devastating than a larger marine spill. The tremendous energies due to thermal mixing, waves, and wind tend to dissipate and otherwise lessen the detrimental local effects of oil pollution in many marine ecosystems (e.g., Owens 1978). Freshwater lakes have a much lower energy input and are confined in space so spilled oil would tend to be concentrated; reliance on slow biodegradation to dissipate oil would probably be more important in lakes than in marine systems. Additionally, hydrocarbons tend to be more soluble in waters with lower salinity (Rossi and Thomas 1981; Rice et al. 1976), so freshwater pelagic organisms would be exposed to higher concentrations of toxic dissolved hydrocarbons. In general, research directly assessing the degree impact crude oil would have on freshwater ecosystems is very limited.

Within the Intermountain West much energy development has recently occurred, with the potential for extensive development in the future. The possibility of environmental damage to freshwater ecosystems due to the establishment of large oil fields is acute. Some areas of high petroleum-related activity also contain large numbers of freshwater lakes. This study assesses the impact of spilled crude oil on two lake ecosystems of the Intermountain region.

The research was conducted in two parts. First, laboratory experimentation explored the effect of two crude oils on two simulated lake ecosystems representing specific hard and soft water lakes. Second, the impact of the two crude oils on the decomposition of aquatic plants in the same two lakes was assessed in field and laboratory experiments. The two segments of this research complement each other by examining different aspects of the effects crude oils would have if spilled on freshwater lakes.

General Objectives

The objective of the portion of the study involving laboratory simulation of lake ecosystems was to determine how crude oil affected an overall ecosystem and its separate components (such as autotrophs, consumers, and decomposers). This was accomplished by documenting changes which occurred within three-phase microcosms in which stable biological communities had developed and then were impacted by crude oils. Changes in aqueous chemistry, nutrient concentrations, gas production and composition, total organic carbon in the aqueous phase and biomass accumulation due to crude oil's impact were determined to assess environmental effects of the oils.

Specific objectives of the experiments involving crude oil's impact on decomposing aquatic plant litter were to determine 1) oil affects on the rate and extent of autothtonous plant litter

decomposition, 2) oxygen utilization rates of oiled and unoiled decomposing litter, 3) nutrient dynamics between the oiled and unoiled litter and its environment, and 4) the duration that crude oil would be expected to exert an impact. Decomposing plant litter has major regulatory functions on lake ecosystems (Carpenter 1980; Landers 1982) and any effect crude oil has on the decomposition process could be ramified over the entire lake. Factors measured to accomplish the goal of assessing oil impacts included 1) the proportion of oiled and unoiled plant litter remaining in two lakes throughout a year, 2) oxygen utilization rates of microbial communities associated with the litter, 3) nutrient content of oiled and unoiled plant litter, and 4) nutrient exchange between the environment and plant litter. The loss of oil from the litter over a year's period was also determined.

LITERATURE REVIEW

Environmental Effects of Oil Pollution

In severe cases, oil pollution has been shown to affect essentially every biotic component of aquatic systems (Southward and Southward 1978; Stebbings 1970; Sanders 1978; Hampson and Moul 1978; Notini 1978; Hyland and Schneider 1976; Mann and Clark 1978). Furthermore, the impact can be of long duration, especially in shallow areas or areas where oil is stranded along the shoreline (Mann and Clark 1978). Ten years or more may be required for a community structure to return to near normal conditions, and sublethal effects may persist much longer (Mann and Clark 1978). Effects of oil pollution on individual components of an ecosystem are highly variable and depend on factors such as climate (Larson et al. 1976, 1977, 1979; Lee et al. 1978; Atlas et al. 1978), physical energy inputs to the system (Owens 1978; Mann and Clark 1978), organism type and feeding habits (Conover 1971; Prouse and Gordon 1976; Wong et al. 1981; Hyland and Schneider 1976), and oil type (Anderson et al. 1974). Effects of oil pollution on different components of an ecosystem will be treated separately in the following sections.

Decomposers

Overall increases in heterotrophic bacterial population levels commonly occur after crude oil enters an aquatic system (e.g., Colwell et al. 1978; Westlake et al. 1978; Atlas et al. 1976). Usually a significant increase in hydrocarbon utilizing bacteria (HCU) results (Colwell et al. 1978; Steward and Mark 1978; Atlas et al. 1978) while some other microbial forms decrease in numbers (Walker et al. 1975; Hodson et al. 1977; Walker and Colwell 1974). Various hydrocarbon compounds are either directly toxic to, or at least actively avoided by, many aquatic microorganisms (Young and Mitchell 1973; Walker et al. 1975; Walker and Colwell 1977; Schindler et al. 1975; Hodson et al. 1977). However, the research of the latter authors was generally conducted on specific groups of organisms and specific hydrocarbons; most research indicates that the general decomposer population (particularly bacteria) quickly respond with increased activity to oil pollution.

Atlas et al. (1978) reported an increase in overall bacteria populations of several orders of magnitude as a result of Prudhoe Crude oil seepage into Prudhoe Bay. Pseudomonas bacteria accounted for a major portion of the overall increase. Concurrently there was a sharp decrease in certain groups of microorganisms. Walker et al. (1975) also reported significant increases in bacteria population when 60 ppm South Louisiana Crude oil was present in an estuary of Chesapeake Bay. Despite the increase in the general bacteria population level, the authors showed definite toxic effects on some bacteria at 60 ppm crude oil in aqueous solution. They concluded that, although overall microbial activity accelerated due to crude oil impaction, the oil was toxic to certain groups of bacteria potentially important to ecosystem functions, such as nutrient cycling, within the estuarine environment. Positive or negative effects were not apparent for other groups of microorganisms, such as yeast and fungi. Finally, Walker et al. (1975) found No. 2 crude oil to limit bacterial populations overall, thus indicating differential effects of different oil types. In another study,

Walker and Colwell (1974) found South Louisiana Crude and No. 2 fuel oil to stimulate bacteria growth over a 28-day period in an environment acclimated to oil contamination, while bacteria populations were depressed at unacclimated sites (all sites were in the vicinity of Chesapeake Bay). Hodson et al.(1977) reported that concentrations above 300 µg/l of four oils (South Louisiana Crude, Kuwait Crude, No. 2 fuel oil, and Bunker C oil) in seawater significantly inhibited marine bacteria activity as measured by D-glucose assimilation. Low concentrations of these oils stimulated bacterial assimilation rates but concentrations of hydrocarbons of 800 µg/l derived from processed oil (i.e., No. 2 and Bunker C oil) inhibited bacteria activity up to 60 percent and hydrocarbons derived from South Louisiana Crude oil reduced activity 17 percent. The highest soluble hydrocarbon concentration reported for seawater is 800 µg/l and was associated with a 2-day old oil spill (Gordon and Prouse 1973).

Generally bacterial population responses to oil pollution are rapid and of long duration. Simulated oil spills in an arctic marine ecosystem increased the numbers of viable heterotrophs and HCU microorganisms 30 days after contamination (Atlas et al. 1978). Lock et al. (1981a, b) investigated effects of a synthetic crude oil on benthic microbial populations in an Alberta river. Lock et al. (1981a) found an increase of from 5 to 9 times the bacteria numbers at the oiled site compared to control sites 30 days after treatment initiation. In a study of longer duration, Lock et al. (1981b) again found increases of bacteria numbers of from 3 to 7 fold due to the synthetic oil. Colwell et al. (1978) noted intermediate to dramatic increases in the number of aerobic microbial heterotrophs at oil polluted sites in the Straits of Megellan 2 years after the grounding of the oil tanker V.L.C.C. Metula. Petroleum degrading bacteria were in much greater numbers at the oiled sites, but the ratio of oil degraders to all other groups was not significantly different between oiled and unoiled sites. There was, however, a major difference in the relative abundances of other bacteria groups (e.g., starch hydrolyzers vs. chitin digesters) and this was attributed to the continuing presence of oil residue in the sediment (Colwell et al. 1978). Steward and Mark (1978) reported decreases in the proportion of HCU bacteria over a 6 year period in Chedubucto Bay, Nova Scotia, following a major oil spill. HCU bacteria decreased from 15 percent of the microbial population shortly after the spill to background levels 18 months later. An extensive survey 6 years later indicated the HCU percentage to be at background levels for 77 out of 79 formerly oiled sites. The authors concluded that the metabolically degradable oil fraction was utilized when HCU bacteria levels reach background levels (Steward and Mark 1978).

In summary, certain microbial populations have been shown to be harmed by toxic components of crude oil. However, crude oil stimulates the overall microbial population to rapidly reach high densities and causes more of the community to be capable of utilizing hydrocarbons. Microbial populations subsequently decline to before impact levels after all metabolically available hydrocarbons are degraded (this does not imply complete removal of the oil). The duration of this cycle apparently depends upon the amount and type of oil spilled, the ecosystem type, and various climatic factors.

Autotrophs

Autotrophic growth may be stimulated or depressed by oil impacts. Blott et al. (1976) reviewed a number of laboratory physiological studies dealing with oil toxicity on algae. They reported that hydrocarbons present in the water column can have a wide range of both stimulatory and inhibitory effects on phytoplankton. Blott et al. (1976) investigated benthic algal

communities in a Delaware river marsh and found that exposure to oil depressed community primary productivity but the degree of effect depended on the kind and concentration of oil used in the experiment. All benthic algal communities eventually recovered from oil exposure, but the species composition of the community was different from that before exposure (Blott et al. 1976). In general, the first group of algae to recover after exposure to crude oil was the blue-green algae. The oils Blott et al. (1976) used were No. 2 fuel oil, Nigerian Crude oil, and used crankcase oil in a range of concentrations of from 1:100 to 1:1000 (V:V).

Inshore algal populations of the Agean Sea including species of diatoms, dinoflagellates, u-flagellates, co-celithophores, silicoflagellates, and blue-green algae all resisted oil toxicity at a total concentration (i.e., dissolved plus particulate) of 27 mg/l (Ignatiodes and Minicas 1977). Oil input was continuous at the site so the algal community was likely well acclimated.

Gordon and Prouse (1973) determined that the degree of growth inhibition exerted by three oils (Venezuelan Crude, No. 2, and No. 6 fuel oils) on a natural phytoplankton community of Bedford Bay, Nova Scotia, was directly proportional to oil concentration in the water. At concentrations below 50 µg/l of Venezuelan Crude phytoplankton growth was actually stimulated. The stimulation was most likely due to inorganic nutrients released from other organisms killed by the crude oil. Present oil levels of the seawater in the region of this research could only decrease overall phytoplankton photosynthesis by a few percent (Gordon and Prouse 1973).

Other studies have found that although oil may be toxic to certain species of planktonic algae, phytoplankton usually recover rapidly after oil exposure due to their high reproductive rates and high mobility (Hyland and Schneider 1976). Benthic algae are usually more severely affected because they are sessile, or relatively immobile, and cannot escape the pollution. Oil also persists much longer in the sediment than it does in the open water (Hyland and Schneider 1976). Reported rates of recovery for oil-impacted benthic communities range from weeks to 5 years; the fastest recovery occurs on rocky, wave battered shores and the slowest in soft-bottom sheltered areas (Hyland and Schneider 1976). Conversely, some studies report benthic periphytic algae stimulation due to oil impacts (Lock et al. 1981a and references within).

Bioassays often show an initial retardation of algal growth followed by a recovery if the oil contamination is only moderate. The algal growth has a lengthened lag phase followed by an exponential growth phase with a depressed slope relative to unoiled controls (Vandermeulen and Ahern 1976). However, if the culture is allowed to grow for sufficient time, the ultimate biomass in oil treatments and unoiled controls approach the same level. Vandermeulen and Ahern (1976) stress species specific responses to oil impaction and suggest that some of the stimulatory response of algae to oil may be due to a mutagenic effect.

Kauss and Hutchinson (1975) showed that aqueous extracts of seven different Western Canadian crude oils and one refined oil product exhibited marked differences in toxicity effects on Chlorella vulgaris Beijerinck. The eight oil extracts reduced cell growth of algae from 5 to 41 percent during the first 48 hours. However, the toxicity was short-lived, resulting only in a lengthening of the lag phase of growth for the algae culture, and was followed by the normal growth pattern. Kauss and Hutchinson (1975) determined that the recovery after the prolonged lag phase was due to volatilization of highly volatile, toxic compounds in the oil extract during the first 24 hours.

A significant growth stimulation was observed for three of the oil extracts after their volatile, toxic compounds had evaporated (Kauss and Hutchinson 1975).

Vascular plants are also reported to have varying responses to crude oil impacts. Burk (1977) reported a lower species diversity and overall plant cover density due to an oil spill during a 4 year study of vascular plants in a freshwater marsh in Massachusetts. Marsh plants were acutely affected, as measured by a reduction in plant species diversity, in Winsor Cave, Massachusetts, throughout a 3 year study following a No. 2 fuel oil spill (Hampson and Moul 1978). Marsh grasses at the site were unable to recolonize by either reseeding or rhizome growth. Conversely, Spartina altemiflora Loisel tolerated up to 8 liters of a Louisiana Crude oil per square meter of marsh surface without a decrease in above ground biomass or new shoot generation in a Louisiana salt marsh (Delaune et al. 1979). Up to 32 ℓ/m^2 of the crude oil did not affect the above ground biomass in greenhouse experiments but recruitment was curtailed at application rates of 4 and 8 ℓ/m^2 and eliminated at 16 and 32 ℓ/m^2. Lower levels of new-shoot generation in the greenhouse experiment at application rates which had no effect in the marsh was attributed to the necessity of the new shoots to "grow through" an oil slick. Wind and other physical forces "broke up" the slick in the marsh (Delaune et al. 1979).

Existing literature concerning oil impacts on autotrophs is confusing because studies seem to contradict one another. Factors contributing to the apparent contradictions include: different studies use different oil concentrations and types, various plant species have different levels of tolerance to oil pollution, physical energy input varies among studies, chemical and other environmental conditions vary among studies, and laboratory conditions also vary. Michael and Brown (1978) and Hsiao et al. (1978) reviewed experimental conditions known to affect experimental results concerning oil pollution studies.

Invertebrates

Planktonic invertebrates are locally affected by crude oil but the overall impact on a large system is generally minimal and recovery rates are rapid. Conversely, benthic invertebrates can be devastated and recovery can be very slow (Hyland and Schneider 1976). One reason for the difference is greater mobility of planktonic and organisms. A second reason is that benthic organisms have more contact with, and may even feed on, contaminated sediment (e.g., Roesijadi et al. 1978; Gilfillan and Vandermeulen 1978; Stainken 1978). Thirdly, the sediments remain contaminated for a longer period of time than does the pelagic zone (Prouse and Gordon 1976). Fourthly, a major portion of the oil entering marine systems (especially coastal areas) becomes incorporated into the sediment and thus contacts the benthic organisms (Prouse and Gordon 1976).

Although oil pollution impacts are less for zooplankton than for benthic organisms, local short-term impacts can be substantial. Wong et al. (1981) studied the effects of pelagic oil pollution on the freshwater daphnia, Daphnia pulex. Oil, in two forms, affected this filter feeding animal. The first form was oil broken up by wave action and dispersed within the water in particles of sizes similar to phytoplankton (i.e., 10-100 μm), and the second was oil which had previously been assimilated by phytoplankton and subsequently ingested by the daphnia. Effects of the small dispersed crude oil particles on the daphnia were specifically studied by Wong et al. (1981). They found that oil exerted a direct toxic effect on the metabolism of the daphnia and interfered with the animal's normal feeding activities by physically clogging filtered appendages. Oil

weathered for 24 hours had approximately 50 percent of the detrimental effect of the fresh oil (Wong et al. 1981). Oil concentrations of up to 5 ppm had no effect on the survival of individual daphnia, but concentrations as low as 1 ppm of both fresh and weathered oil reduced the daphnia's fecundity. Concentrations of fresh oil of 50 and 100 ppm resulted in total mortality within 168 and 72 hours, respectively (Wong et al. 1981).

Much of the oil entering an aquatic system ends up in the sediment and takes a long time to degrade. Prouse and Gordon (1976) suggested that the response of benthic organisms is the most accurate measure of the oil spill's impact. Furthermore, since the highly toxic compounds are not present for a long time period even in the sediment, but other hydrocarbons do persist, sublethal effects on benthic organisms are potentially very important (Percy 1977).

Prouse and Gordon (1976) determined the quantities of oil in the sediment which adversely affect the marine polychaete (Arenicola marina). Concentrations of fresh oil (Kuwait Crude) in excess of 100 µg oil per gram sediment force the polychaete to leave its borrows and cease feeding (this organism ingests sediment). Oil concentrations as low as 10 µg oil/g sediment reduced the rate of cast production, and presumably feeding activity. To put these concentration values in perspective, oil concentrations from 10 to 3,000 µg/g sediment were found in areas impacted by the oil tanker Arrow 2 years after it stranded (Hargrave and Phillips 1975).

The duration of sublethal effects on benthic invertebrates was illustrated by a study on a marine soft-shelled clam by Gilfillan and Vandermeulen (1978). Six years after the original contamination, the clam population was still below normal. Tissue concentrations of hydrocarbons were as high as 200 µg/g tissue, and growth rates were below normal. The authors did not predict how much longer these detrimental sublethal effects would persist.

An amphipod (Anisimus affinis) had the ability to distinguish between uncontaminated and lightly oiled sediments, and it selected the uncontaminated sediment. However, when the sediment was heavily oiled the amphipod's chemoreceptive abilities were impaired to the extent that selective abilities were lost (Percy 1977). Thus in a lightly oiled environment the amphipod might survive by selective movement and feeding, but with more oil it probably could not persist. Another amphipod and two isopod species were also tested but lacked the ability of the Anisimus affinis to distinguish between oiled and unoiled sediment (Percy 1977).

Vertebrates

Fish and bird kills resulting from oil spills attract media attention, but with the possible exception of benthic fish kills, are poor indices to the overall environmental damage. A portion of the pelagic fish population can emigrate from an area impacted by petroleum and recolonize the same area after natural weathering processes (which are fairly rapid in the open water) make the area suitable again. In contrast, benthic fish are less apt to migrate and their intimate contact with sediment (where contamination persists for years or decades) makes them more susceptible to oil pollution (Hyland and Schneider 1976).

Some marine birds are also susceptible to oil pollution for the following reasons. First, they are often weak flyers and not prone to emigrate from the area (e.g., auks and penguins). Second, they are gregarious, therefore, a large local population can be affected at once. Third, many birds dive after prey and come in extended contact with oil. The following factors have been shown to cause oil pollution

related deaths in birds. Disruption of feathers can lead to loss of buoyancy and possible drowning. Pneumonia can develop after an oil coating on the feathers results in loss of insulation. Toxic oil can be ingested due to excessive preening and cause metabolic toxicity to the birds. Finally, starvation can be accelerated because the birds increase their body metabolism to maintain body heat concomitant with decreased food intake due to the oil pollution problem (Hyland and Schneider 1976). Attempts to recover seabirds after oil pollution impacts an area have been largely unsuccessful (Clark 1978).

Concentrations of petroleum hydrocarbons that have affected several fish species have been determined in laboratory bioassay tests. In a series of static bioassay tests involving numerous marine animals, fish were consistently among the most sensitive species to Cook Inlet Crude oil and No. 2 fuel oil (Rice et al. 1976). Ninety-six hour TLm's ranged from 0.81 to 2.74 ppm of the hydrocarbons. The authors note that 24-hour TLm's were very nearly the same value as the 96-hour test because evaporation and biodegradation reduced the oil concentration later in the experiment (in fact, most of the damage was done to the fish within the first 2 hours). In another study, concentrations of the water soluble fraction of a South Louisiana Crude oil were lethal to 50 percent of three Texas coast estuarine fishes (Menidia beryl-liona, Fundulus similus, and Cyprinodon variegatus) at concentrations of from 8.7 and 19.8 ppm (Neff et al. 1976).

Sublethal effects of petroleum hydrocarbons on fishes are also an important consideration. The English sole (Parophrys vetulus) exposed to 700 µg of Alaskan North Slope Crude oil per gram dry sediment for 4 months accumulated alkanes and aromatic compounds in its skin, muscle, and liver. Also many of the flatfish lost weight during the exposure and developed severe hepatocellular lipid vacuolization. As the concentration of hydrocarbon decreased in the experimental aquaria, tissue levels of hydrocarbon in the flatfish also decreased (McCain et al. 1978). Stegeman and Sabo (1976) noted that petroleum hydrocarbon concentrations of less than 200 ppb altered the lipid metabolism of two fish local to the Cape Cod area, the implication being that sublethal effects were interfering with normal metabolic processes.

Physical Factors Affecting Oil Weathering

The physical environment at the site of an oil spill affects the degree, type, and duration of impacts. Important factors include climate (e.g., temperature and sunlight intensity); wind, waves or turbulence in the environment, and substrate type.

The climate of an area can have profound effects on the severity of an oil spill; especially when considering the duration of impact. In general, oil pollution problems are more devastating and of longer duration in colder climates (Rice et al. 1976). Low temperatures slow oil weathering by: 1) Reducing oil biodegradation rates and thus making harmful hydrocarbons more persistent (Atlas et al. 1978; Rice et al. 1976; Atlas and Bartha 1972). 2) Increasing the solubility of some hydrocarbons. Gordon et al. (1973) found oil concentrations to decrease by a factor of two when the water temperature was raised from 1-2°C to 19-21°C. In part, this may have been due to reduced evaporation at lower temperatures (Atlas and Bartha 1972). 3) Restricting evaporation of the highly toxic lighter hydrocarbons if ice forms over an area impacted by an oil spill. Atlas et al. (1978) found highly toxic light compounds to persist at least 3 weeks in water under ice. The same types of compounds evaporate within 24 hours without the ice cover (Kauss and Hutchinson 1975). 4) Life cycles of

biota in cold climates tend to be longer than in warm climates, thus the recovery of populations of aquatic organisms requires more time after destruction by an oil spill (Hyland and Schneider 1976).

Sunlight is a climatic factor which may have subtle, yet potentially important, effects on the impact of an oil spill. Exposure of oil to sunlight may convert the original hydrocarbons into forms much more destructive to pelagic biota (Larson et al. 1976, 1977, 1979; Lee et al. 1978). Resulting compounds include peroxides, carbonyls, phenols (Larson et al. 1976, 1977), and various organic acids (Larson et al. 1979). The longer the duration of radiation, the greater the concentration of these compounds. Larson et al. (1979) suggest that these toxic compounds are formed as light catalyzes a reaction which incorporates oxygen into the hydrocarbon. Oxygen necessary for the reaction is concentrated on the oil slick surface by nonpolar liquids in the oil (Larson et al. 1976). Compounds resulting from the photooxidation reaction are not necessarily more toxic to aquatic organisms than their precursors but their solubility is greatly increased due to a greater polarity so pelagic organisms are more directly exposed to the toxic components (Larson et al. 1979). In a series of bioassay tests, toxic effects on yeast resulted at concentrations of photooxidized hydrocarbons less than 10^{-4} M. Toxic concentrations resulted after 15-24 hours of irradiation (Larson et al. 1976). Lee et al. (1978) found photooxidation to be an important removal mechanism for heavier aromatic compounds. For example, up to 50 percent of the initial concentration of benzo(a)pyrene was photooxidized within 17 days in in-situ enclosures.

Wind intensity and duration also have important effects on petroleum degradation and transfer in aquatic systems. Wind increases the rate of hydrocarbon volatilization. Since the hydrocarbons most susceptible to evaporation are those which are most toxic, their rapid evaporation lessens detrimental impacts on the biota (Atlas et al. 1978). Increased wind also causes increased turbulence and greater oil dissolution (Michael and Brown 1978; Boylan and Tripp 1971; Gordon et al. 1973). Dissolved hydrocarbons are largely responsible for the detrimental effects on pelagic organisms, so short-term increases in toxicity might result from winds. Wind also tends to break up surface oil slicks, mix small particles of oil into the water, and thus can be detrimental to filter feeding zooplankton (Wong et al. 1981). The length of time particulate oil remains dispersed in the water depends on the particle size, its specific density, water temperature, and degree of water turbulence. Stokes' Law can be used to predict particle residence time in the water column (Gordon et al. 1973). Wind can also transport oil contaminated sediments to different locations in the water body, having the effect of lessening peak concentrations of oil but spreading the pollution over a larger area (Myers 1976). Sediment-petroleum interactions will be reviewed in greater detail in a later section.

Waves, created by thermal currents and wind, also have a significant effect on the degree and type of environmental damage caused by oil pollution. Waves tend to break up and disperse oil and place it in contact with the sediment (Owens 1978; Southward and Southward 1978; Mann and Clark 1978). Many of the considerations concerning oil pollution and wind, reviewed above, also apply to oil pollution and waves.

In short, environmental conditions influence reaction rates and the degree of hydrocarbon transfer between reservoirs within the aquatic system (Kolpack and Plutchak 1976). In this context "reservoirs" refer to the water surface, water column, bottom sediment, atmosphere, and near shore zone of the water body.

Mechanisms of Oil Weathering

Mechanisms by which petroleum hydrocarbons are weathered in aquatic ecosystems include; evaporation or volatilization, dissolution, sedimentation and sediment transport, and biodegradation.

Evaporation

Evaporation of highly volatile, and usually highly toxic, compounds from oil spilled in aquatic environments is a critical phase of weathering which renders remaining oil less toxic (Vandermeulen and Ahern 1976; Atlas et al. 1978; Knap and Williams 1982; Michael and Brown 1978; MacKay and Wolkoff 1973). Vandermeulen and Ahern (1976) cite evaporative losses of No. 2 fuel oil and Kuwait Crude in bioassay flasks of up to 90 percent in 2 weeks. Atlas et al. (1978) report more conservative loss estimates of 22 percent for Prudhoe Bay oil in the first month in an arctic environment. In laboratory experiments, Knap and Williams (1982) observed a 15 percent decrease of hydrocarbons in aqueous medium after 24 hours, and a 30 percent decrease after 40 days. With aeration, hydrocarbon losses increased to 60 percent. Lee et al. (1978) reported different rates of evaporative loss for different hydrocarbons in aqueous medium. Highly volatile hydrocarbons (e.g., benzene, toluene, ethylbenzene, xylene, and trimethylbenzene) were present 1 day after a simulated spill of aromatic hydrocarbons but absent after 3 days. Less volatile hydrocarbons (e.g., naphthalene, methylnaphthalene, dimethylnaphthalene, anthracene, fluoranthene, benz(a)anthracene, and benzo(a)pyrene) decreased exponentially throughout the 17-day experiment. The latter compounds had half lives of 3 to 6 days in solution (Lee et al. 1978). For heavy oils (e.g., No. 5 fuel oil with component hydrocarbons of more than 15 carbon atoms) evaporative losses are of minimal importance to the weathering of oil spills in the natural environment (e.g., Cretney et al. 1978; Shelton and Hunter 1974).

The most rapid evaporation is for volatile, low weight hydrocarbons with less than 20 carbon atoms per molecule (Vandermeulen and Ahern 1976; Knap and Williams 1982). For the refinery effluents into an estuarine environment studied by Knap and Williams (1982) hydrocarbon loss within the first 24 hours was confined to aliphatic and low weight aromatic compounds. Cretney et al. (1978) reported evaporation of n-alkanes and light aromatic oil fractions during the first 5 days of a No. 5 crude oil spill on the British Columbia coast.

In summary, evaporation is a critical detoxifying step of petroleum weathering, especially for oils with a substantial low molecular weight fraction. For such oils a substantial part is lost by evaporation, and the most toxic compounds are lost first.

Dissolution

Dissolution of hydrocarbons from surface oil slicks is generally fairly limited and selective; aromatic compounds are less hydrophobic than aliphatic so go into aqueous solution more readily (Gearing et al. 1980; Kauss and Hutchinson 1975). The dissolution of low molecular weight (C_1-C_4) and volatile liquid hydrocarbon (C_5-C_{14}) was studied from a subsurface oil spill in the Gulf of Mexico. Directly under the spill, the concentration of volatile liquid hydrocarbons reached only 400 µg/l and dissipated quickly by evaporation. Within 21 miles of the oil slick, all hydrocarbons with 12 or fewer carbon atoms in their molecule were lost (Brooks et al. 1981). The highest reported concentration of dissolved hydrocarbons located by this literature survey was 800 µg/l, and it occurred 25 cm under a 2-day oil slick (Gordon and Prouse 1973).

Although hydrocarbons in aqueous solution are detrimental to pelagic

organisms, weathering processes occur faster when the oil slick is dispersed. Chemical dispersants are sometimes used to break up oil spills by causing hydrocarbons to become more soluble and thus more quickly weathered and easily transported from the impacted site (McAuliffe et al. 1980). Increased apparent aqueous solubility of hydrophobic organic compounds also can result if dissolved organic matter is present in the water and becomes bonded (or associated) with the hydrocarbons. In one study, fulvic acid in a marine system increased the solubility of several alkanes (hexadecane, eiosane, and pristane) but did not affect the solubility of the aromatic compounds (phenanthrene and anthracene) investigated. The increased solubility of hydrophobic organic compounds is a result of the surfactant characteristics of dissolved organic matter. Hydrophobic sites (e.g., alkyl chains) of the hydrocarbon become associated with the natural organic matter resulting in a complex held in solution as a colloidal dispersion (Hassett and Anderson 1979).

Two important petroleum weathering mechanisms, evaporation and sedimentation, which tend to counteract dissolution are reviewed separately.

To summarize, crude oil dissolution into water causes higher toxicity to pelagic organisms but increases the rate of oil weathering. In general, aromatic compounds are more soluble than aliphatic compounds of similar molecular weight, although artificial or natural dispersants alter the relative solubilities.

Sedimentation

Long-term effects of accidental oil spills on aquatic systems may primarily depend on the amount of oil adsorbed onto sediment particles and incorporated into the bottom sediment (Zürcher and Thüer 1978). Mechanisms by which oil hydrocarbons reach the sediment include: 1) hydrocarbon adsorption onto suspended sediment which subsequently sinks to the bottom (Gearing et al. 1980), 2) agglomeration of suspended oil particles into larger particles which sink (Zürcher and Thüer 1978), and 3) ingestion of oil particles, or oil contaminated particles, by zooplankton followed by sedimentation of the animals' excreta (Lee 1976; Corner and Harris 1976; Wong et al. 1981; Conover 1971).

Disturbed sediments absorb dissolved oil from an aqueous solution and have a cleansing effect on the water in the proximity of the spill (Myers 1976; Teal et al. 1978; Gearing et al. 1980). Adsorption of hydrocarbons onto sediment from the aqueous phase is rapid (Knap and Williams 1982). Zürcher and Thüer (1978) determined that the amount of oil adsorbed onto kaolinite clay suspended in water reached a constant value after 10 minutes of exposure in experimental flasks. In another laboratory study, 95 and 99 percent of the hydrocarbon adsorption on sediment occurred within 18 hours after the oil was added at low and high concentrations, respectively (Knap and Williams 1982). Seventy percent of the oil added by Knap and Williams (1982) was recovered from the sediment after the experiment.

Equilibrium isotherms, such as Freundlich isotherms, were successfully used to describe the adsorption of substituted polynuclear hydrocarbons onto sediment particles (Mean et al. 1982). Other studies found a limit to the amount of hydrocarbon that can be adsorbed by sediment (Knap and Williams 1982; Zürcher and Thüer 1978). Zürcher and Thüer (1978) reported that 20 mg/l of kaolinite clay adsorbed 4 µg/l hydrocarbon in their experimental system.

Factors which determine the rate and extent of hydrocarbon adsorption onto sediment include: organic matter content on the sediment (Myers 1976; Mean et al. 1982; Knap and Williams 1982), sediment grain size (Myers

1976), and the hydrocarbon compounds involved (Zürcher and Thüer 1978; Knap and Williams 1982; Gearing et al. 1980). Increased organic matter content increases the sediment's capacity for hydrocarbon adsorption (Myers 1976; Mean et al. 1982; Knap and Williams 1982) although the mechanism is unknown (Mean et al. 1982). Myers (1976) reports that equal weights of smaller-sized suspended particles sorbed more hydrocarbons than larger-sized particles. The difference is probably mostly due to the larger surface area for a given weight of the smaller sediment particles, although mineralogical factors might also be important. The type of hydrocarbon is extremely influential on the degree of its adsorption onto sediment. Gearing et al. (1980) found that less soluble hydrocarbons were preferentially removed by sediment adsorption. Sedimentation removed 50 percent of the relatively insoluble, saturated hydrocarbons but only 20 percent of more soluble aromatics. In general, aliphatic hydrocarbons adsorb more readily onto sediment than aromatics because the hydrophobic nature of many aliphatic compounds makes their attraction to sediment more powerful than their solubility in water (Knap and Williams 1982). Low values for heats of adsorption indicate weak, nonchemical attractions between the hydrocarbons and minerals, but even this weak attraction favors a hydrocarbon-sediment interaction over a hydrocarbon-water association (Myers 1976).

Agglomeration is another mechanism by which petroleum is deposited in the sediments underlying aquatic systems. Oil dispersed through turbulence is drawn into droplets by interfacial tension. The oil particles then agglomerate, sink to the bottom, and become entrapped in the sediments (Zürcher and Thüer 1978).

Zooplankton ingestion of oil, or oil contaminated particles, can lead to oil sedimentation via the animals feces. Conover (1971) estimated that as much as 10 percent of the No. 2 fuel oil released into Chedubucto Bay after the grounding of the tanker Arrow was associated with zooplankton. The feces of the zooplankton contained up to 7 percent oil. Conover (1971) calculated that 20 percent of the particulate oil in the bay was sedimented inside of the zooplankton's feces.

Important environmental consequences are associated with petroleum sedimentation. Whereas sedimentation may lessen adverse effects in the pelagic zone by removing hydrocarbons, it prolongs the impact of an oil spill. Biodegradation of oil within the sediment zone is slower than that in the open water (Prouse and Gordon 1976). Additionally, oil may be leached back to the water, making the sediment a chronic source of oil pollution (Teal et al. 1978). Benthic invertebrates, which are key components of most aquatic systems, are often adversely affected by ingestion, or even contact with, petroleum contaminated sediments (Hyland and Schneider 1976; Prouse and Gordon 1976).

Petroleum biodegradation

The petroleum not removed by the above processes is ultimately dissipated by the process of biodegradation. The amount of oil remaining to be degraded biologically depends on climatic factors of the environment (e.g., temperature, wind and radiant energy intensities), physical energy input to the system, and original oil composition (e.g., Lee et al. 1978; Atlas et al. 1978; Mann and Clark 1978; Owens 1978; Larson et al. 1976, 1977, 1979). The above factors control other oil weathering processes of the petroleum such as evaporation, sedimentation, photooxidation, and dissolution. Factors affecting the rate and extent of petroleum biological degradation include: temperature, aeration, agitation, and nutrient availability (particularly nitrogen and phosphorus) (Blumer and Sass 1972; Atlas et al. 1978; Colwell et al. 1978).

Biodegradation of oil is a slow process. After the processes of evaporation, dispersion, and sedimentation occur, biodegradation is largely confined to the sediment. Most of the activity is at the sediment-water interface and biodegradation essentially ceases in anaerobic sediment (Lee 1976). Blumer and Sass (1972) found that oil penetrated 7.5 cm into the sediment of Buzzard Bay, Mass., 2 years after a No. 2 fuel oil spill. Biodegradation was minimal below 2 cm into that sediment due to oxygen limitation (Blumer and Sass 1972). Many hydrocarbons in petroleum persist in the sediments for years or even decades (Myers 1976; Gearing et al. 1980; Teal et al. 1978).

Bacterial biodegradation selectively removes certain compounds of oil before others. Blumer and Sass (1972) reported decreasing rates of hydrocarbon degradation from n-alkanes to iso- and cyclo-alkanes and finally to aromatic hydrocarbons over 2 years at Buzzard Bay, Mass. Cretney et al. (1978) noted that n-alkanes were completely removed from a system during the first year after an oil spill whereas cyclo-alkanes persisted. Nonalkane compounds with from 28 to 36 carbon atoms were the least susceptible to biodegradation over 4 years (Cretney et al. 1978). Although aromatic compounds are resistant to rapid degradation (Knap and Williams 1982), there is ample evidence that bacteria are capable of oxidizing simple rings such as benzene and benzo(a)-pyrene; evidence for the biodegradation of more highly condensed aromatic rings is uncertain (Gibson 1976). Colwell et al. (1978) suggest biodegradation is less important for aromatic compound weathering than for aliphatic weathering. Most aliphatic compounds eventually biodegrade; but evaporation is probably more important as an ultimate dissipation mechanism of aromatic compounds (Colwell et al. 1978).

Aromatic compounds are particularly long lived in the sediments (Myers 1976; Gearing et al. 1980; Teal et al. 1978). Long-term removal has been shown to be due to diffusion, water solubilization, and evaporation as well as microbial oxidation by Teal et al. (1978) who also studied the fates of two and three ringed aromatic hydrocarbons over a long time period in the sediment of Buzzard Bay, Mass., after a No. 2 fuel oil spill. They determined lighter weight aromatic compounds dissipated from the sediment more rapidly than heavier, more substituted aromatics. In fact, some of the heavier aromatics actually increased in concentration at some sediment depths, probably due to some type of vertical migration (Teal et al. 1978).

Although sediment degradation of petroleum hydrocarbons is slow, it begins immediately after an oil spill (Gearing et al. 1980). Atlas et al. (1978) noted light weight hydrocarbons, which would have evaporated from the water column in days, remained in the sediment 2 months after an oil spill. However, notable changes of sediment hydrocarbon composition demonstrated that weathering was occurring (Atlas et al. 1978).

The formation and sedimentation of tar balls severely slows oil biodegradation (Colwell et al. 1978). The greater surface to volume ratios of the larger particles reduce the biologically active surface and can cause oxygen and nutrient limitations beneath the tar ball surface. Additionally, the tar balls can form an asphalt-like outer cover which is resistant to microbial oxidation (Colwell et al. 1978).

Importance of Decomposing Aquatic Plants in Lakes

The decomposition of vascular aquatic plants can have a substantial environmental impact and be a major regulatory agent on lake ecosystems, especially in lakes with a high proportion of littoral area (Howard-Williams and Lenton 1975). Three ways in which decomposing aquatic plants are important to a lake will be reviewed. First,

nutrient regeneration caused by macrophyte decomposition can provide a substantial amount of inorganic nutrients to the rest of the lake (Carpenter 1980). Second, the decomposing macrophytes can place a very significant oxygen demand on a lake system. Third, decomposing plant material and their attendant microbial population are the major energy source for a number of important heterotrophs.

Aquatic vascular plants "pump" nutrients from the lake's sediments to the water, thus being a significant agent in the lake's internal nutrient cycling process (Barko and Smart 1980; Howard-Williams and Lenton 1975). Several studies have confirmed the importance of the role of aquatic plant roots in absorbing nutrients from the sediments and translocating them to the biomass above (e.g., Demarte and Hartman 1974; McRoy et al. 1972; Bristow and Whitcombe 1971; Best and Mantai 1978; Carignan and Kaulff 1980; Nichols and Keeney 1976). Other studies have shown that even when there are nutrients available in the lake's water, the plant preferentially obtain nutrients from the sediment (Bristow 1975; Bole and Allan 1978). The reducing nature of most subsurface lake sediments causes nutrients, such as phosphorus, to be in a soluble form easily taken up by plants (Barko and Smart 1980). If the lake water is not anaerobic, an oxidized microzone at the sediment surface prevents these nutrients from becoming available to the lake proper by diffusion from the sediments (Mortimer 1941, 1942).

Barko and Smart (1980) studied the nutrient release patterns of three aquatic macrophytes (Egeria densa, Hydrilla verticillata, and Myriophyllum spicatum) which were fully capable of deriving their phosphorus requirement exclusively from the sediment. They determined that phosphorus release occurred primarily when the plants decomposed, so nutrient excretion by living plants was relatively unimportant. With a macrophyte cover of 25 percent (low for many littoral regions) and complete decomposition of the plants, internal loading of phosphorus was 0.60-1.05 g/m^2 for E. densa, 0.1-0.5 g/m^2 for H. verticillati, and 0.15-1.6 g/m^2 for M. spicatum. The higher values for these plants are comparable to external phosphorus loading rates into many eutrophic lakes (Barko and Smart 1980). Phosphorus loading to Goose Lake, Iowa, from decomposing Typha glauca during the first 525 days of decomposition was 0.1 g/m^2, and for nitrogen 7.1 g/m^2 (Davis and Van der Valk 1978).

Macrophyte decay in Lake Wingra, Wisconsin, accounts for 50 percent of the observed dissolved total phosphorus flux between the littoral and pelagic zone of the lake (Carpenter 1980). Thus macrophytes, upon decay, are an important source of phosphorus not only to biota in the littoral region but in the pelagic zone as well. Seventy-five percent of phosphorus in the dominant macrophyte, Myriophyllum spicatum L., is derived from the sediment in Lake Wingra (Carpenter 1981). Therefore, rooted macrophytes are an important link to sediment phosphorus which would otherwise be sealed from the lake proper. In fact, Carpenter (1981) states that the overall metabolism of Lake Wingra is linked to the release of dissolved organic carbon and dissolved total phosphorus from the littoral region.

Howard-Williams and Lenton (1975) also stress the importance of aquatic macrophytes in a large, shallow African lake. They consider the littoral plants of this lake as a major nutrient reservoir for the rest of the lake. Often nutrients are released early in the decomposition cycle but immobilized later. However, the net effect during decomposition is nutrient release as observed in Lake Chilwa of Malawi, Africa (Howard-Williams and Howard-Williams 1978) and other lakes for which this has been studied (e.g., Carpenter 1980, 1981; Jewell 1971; Howard-Williams and Davies 1979).

Nutrient release from decomposing plants is unevenly spaced over the time period of decomposition. Generally, release rates are very high initially but later drop (Howard-Williams and Junk 1976). Over 50 percent of the total phosphorus stock of Potamogeton pectinalius was lost during the first 7-15 days of decomposition in Swartulei, an oligotrophic Southern African coastal lake (Howard-Williams and Davies 1979). The authors hypothesize, based on this and other studies, that decomposing macrophytes are more likely to act as a nutrient source in oligotrophic than in eutrophic lakes. Jewell (1971) reported initial nutrient regeneration rate of 4.9 and 5.8 percent per day for nitrogen and phosphorus, respectively, from various aquatic macrophytes in a laboratory study. Here, regeneration rate is defined as the percent of nutrients released from the plant material relative to the total available amount at the onset of decomposition. Sudo et al. (1978) also reported high initial nutrient release rates for decomposing plants of the Tama-gawa, a shallow river running through Tokyo. Total phosphorus and total nitrogen regeneration rates were 75 and 62 percent, respectively, for the first 50 days of decomposition.

Phosphorus is more rapidly released from decaying plants than nitrogen because nitrogen is immobilized by the decomposing microorganisms for growth (Nichols and Keeney 1973). Although nitrogen is more often limiting to decomposers (Parnas 1975; Nichols and Keeney 1973; Carpenter and Adams 1979; Anderson 1973), phosphorus limits overall productivity in most lakes (e.g., Wetzel 1975). Thus phosphorus regeneration via decomposing macrophytes can substantially affect lakes productivity.

Macrophytes exert a biological oxygen demand on the lake or river in which they are decomposing (Jewell 1971; Sudo et al. 1978). The aquatic plants studied by Jewell (1971) required from 1.17 to 1.87 grams of dissolved oxygen for each gram of plant material oxidized (the average was 1.30). Sudo et al. (1978) found an average oxygen requirement of 1.20 grams per gram periphytic algae oxidized. During the initial stages of decay, the aquatic plant oxygen utilization rate was about half that of domestic sewage. Using this utilization rate and a plant density of 500 grams ash free weight per meter squared (not unreasonable for littoral zones in lakes), Jewell (1971) calculated the initial oxygen demand from one hectare of lake area, if all plants began to decompose at once, to be comparable to raw domestic sewage from 24,000 people. Obviously, this is a "worst case" example, normally all plants would not begin decomposing simultaneously unless impacted by a highly toxic substance (e.g., a herbicide or perhaps a petroleum spill). The potential oxygen demand impact is illustrated by a small lake which was subject to herbicide treatment; 4 days after herbicide treatment the dissolved oxygen of the entire lake was zero, and the lake remained anoxic for 2 days (Jewell 1971). The environmental effect of this is not only on the present biota but is a long term impact through the release of undesirable reduced chemicals from the sediment (see Mortimer 1941, 1942).

A third important environmental consequence of decomposing aquatic plants is that they form detritus. In this sense detritus can be taken as the decomposing plant material plus its attendant decomposer microflora. This detritus provides energy to a variety of aquatic macroinvertebrates (Lopez et al. 1977; Hargrave 1970a, b; Fenchel 1970, 1972). In turn, macroinvertebrates perform important ecosystem functions in lakes (see Werner 1979 for a literature review) as well as being critical food items for higher trophic levels. In short, plant litter goes into the formation of detritus which has long been considered central to lake metabolism (e.g., Lindeman 1942;

Odum 1971; Wetzel 1975; Rich and Wetzel 1978).

Factors affecting decomposition rates of aquatic plants

Widely varying decomposition rates are presented in the literature for aquatic macrophytes. Some factors affecting the rate of decomposition are ambient temperature, nutrient availability in the plant litter and its environment, biochemical composition of the plant litter, particle size of the plant material, and the presence of macroconsumers.

Temperature is a key factor determining the rate of plant litter decomposition because it regulates the activity of heterotrophic microorganisms (e.g., Bunnell et al. 1977; Flanagan and Bunnell 1975; Boyd 1970; Gosz et al. 1973). In general, the rate of plant decomposition increases with increasing temperatures to an optimal temperature of 28 to 31°C after which the rate drops quickly (Carpenter and Adams 1979; Carpenter 1980). A convenient measure of rate differences due to temperature differences is the Q_{10} value defined as $(K_1/K_2)^{10/T_1-T_2}$, where "K_1" is the rate coefficient associated with temperature "T_1," and "K_2" is associated with "T_2." Heterotrophic processes commonly have Q_{10} values of 2.5 to 3.0 when temperatures are measured in degree centigrade (Carpenter and Adams 1979). A Q_{10} of 2.5 means that biological activity increases 9.6 percent per degree centigrade. Carpenter and Adams (1979) found a Q_{10} of 3.0 for the decomposition of Myriophyllum spicatum in Lake Wingra, Wisconsin. Recently it has become clear that a single Q_{10} value over wide temperature ranges inadequately describes the effect of temperature; a degree change in one temperature range can have a different magnitude of impact on biological activity than a degree change in another range (see Thornton and Lessem 1978; Grenney and Kraszewski 1981; Schneiter and Grenney in press). For this reason, a continuous function relating decomposition decay coefficients to temperature is desirable (see Carpenter and Adams 1979; Carpenter 1980).

Nutrient availability is a second factor which influences the rate of plant decomposition. Howarth and Fisher (1976) found that by increasing nitrogen and phosphorus levels in the water of stream microecosystems the rate of leaf decomposition was also increased. Nichols and Keeney (1973) determined that microorganisms decomposing Myriophyllum exalbescens in a laboratory experiment were nitrogen limited; and as soon as nitrogen became available, it was immobilized by the microorganisms. Nitrogen addition, as nitrate or organic nitrogen, stimulated decomposition of Myriophyllum spicatum but phosphorus addition had no effect (Carpenter and Adams 1979). Anderson (1973) and Parnas (1975) stressed nitrogen as the limiting nutrient in plant litter decomposition.

The nitrogen content of the plant litter itself, along with nitrogen concentrations of the ambient medium, is considered important by many investigators to the rate and completeness of decomposition (Carpenter and Adams 1979; Gosz et al. 1973; de la Cruz and Gabriel 1974; Nichols and Keeney 1973). Carpenter and Adams (1979) found nitrogen content and water temperature to be the most useful parameters to predict decay rates of plant litter. Gosz et al. (1973) report increasing levels of nitrogen in litter to be well correlated with faster decomposition rates. The authors found that while phosphorus was rapidly leached from decomposing litter, much of the nitrogen was immobilized by the decomposers as soon as it was released from the plant litter. The result of nitrogen immobilization is a decreasing carbon to nitrogen ratio (C:N) through time. Boyd (1971) noted C:N ratios decreased from 26.7 to 11.3 during the decomposition of Juncus effusus. Nichols and Keeney (1973) and de la Cruz and Gabriel (1974) also report increases in nitrogen relative to

other components in decomposing litter. In contrast, Hunter (1976) reported different trends for the C:N ratio through time for three plants (Chara contraria, Lemna minor, and Fucus vesiculosus) and two habitats. Chara began with a high C:N ratio which decreased through time while Lemna initially had a low C:N ratio that increased through time. The C:N ratios for Chara and Lemna converged to a single value toward the end of the decomposition cycle. The C:N ratio for Fucus decreased in two different habitats, but to a greater extent in one. Hunter (1976) concluded the plant nutritional values (for which the C:N ratio is an index) converge as decomposition proceeds and the final C:N ratio may be more dependent on the nature of decomposer communities than the nature of the organic material undergoing decomposition. The C:N ratio of eelgrass (Zostera marina) remained constant throughout an entire decomposition cycle (Harrison and Mann 1975b). Thus C:N ratio values are plant, time, and habitat dependent; and comparisons among sites and studies are difficult. Smith and Douglas (1971) also concluded that the C:N ratio may not be a good index to decomposibility or the stage of decomposition. Although nitrogen addition stimulated decomposition in every paper reviewed, C:N ratio trends through time are not consistent. Apparently, either all the nitrogen released from the litter of all plant species is not available to decomposer organisms or somehow the litter released nitrogen is not conserved at the site of decomposition. In either case, the C:N ratio may not be as valid an index of the stage of decomposition as sometimes claimed.

The biochemical composition of plants is quite variable (Adams et al. 1973; Boyd 1968, 1969), and this affects the rate and completeness of the decomposition of the litter (Godshalk 1977). The biochemical composition of plants is largely dependent upon the plant species plus environmental and seasonal factors (Boyd and Hess 1970).

In part, biochemical composition of plants is a function of their growth form and habitat. For example, emergent aquatic plants (e.g., Typha) are not supported by an aqueous medium so require more supportive tissue than submerged (e.g., Potamogeton) or floating (e.g., Nuphar) aquatic plants (Godshalk 1977; Howard-Williams and Davies 1979). Supportive tissues are some of the most resistant tissues to biological degradation; therefore, emergent vegetation is expected to be more resistant to decomposition than are submerged aquatic plants. This is illustrated by the half-lives of several aquatic plants reported by Howard-Williams and Davies (1979) in a review of the literature. Half-life is that time required to decompose the first one-half of a given mass of plant litter and is defined as "ln 2/K" where "K" is the decomposition rate constant in days. In two African lakes, Typha (an emergent) had a half-life of 93 days, and Potamogeton's (a submergent) half-life was 35 days. Typha had a half-life of 180 days in a South Carolina impoundment while Myriophyllum's half-life was 20-45 days in Lake Mendota, Wisconsin. Harrison and Mann (1975a) found the decay of structural carbohydrates to be the rate limiting step to the decomposition of the emergent eelgrass, Zostera marina L. Almazan and Boyd (1978) reported higher cellulose content in plant litter was correlated with lower rates of decay. Cellulose content is often associated with structural strength in plants.

The effect of plant litter particle size, and the presence of macroconsumers on litter decomposition rates are related since macroinvertebrate activity is a major mechanism reducing the particle size of plant litter. Reducing the particle size increases the surface area on which decomposers can act; thus the rate of decomposition is increased (Fenchel 1970; Harrison 1977; Lopez et al. 1977).

Macroinvertebrate activity also increases the rate of plant litter decomposition by increasing the rate of critical nutrient turnover to the decomposers (e.g., Johannes 1964, 1968). Macroconsumers also graze bacteria populations which decompose litter, thus creating a physiologically younger and more active bacteria population which increases the rate of litter decomposition (Harrison and Mann 1975a; Barsdate et al. 1974).

Stages of decomposition

Plant litter is considered to decompose in three phases; a leaching phase, biodegradation of the majority of plant material, and biodegradation of more refractory plant material (Godshalk and Wetzel 1978b). The first stage involves autolysis and leaching, during which highly soluble organic and inorganic material is physically washed from the litter (Golterman 1977; Boyd 1970). Up to 65 percent of organic material may be lost by leaching (Harrison and Mann 1975a) although the amount is usually between 0 and 20 percent (e.g., Boyd 1970; Davis and Van der Valk 1978; Godshalk and Wetzel 1978b; Howard-Williams and Howard-Williams 1978; Mason and Bryant 1975). The leaching period for aquatic plant litter may last from several hours to 20 days (Howard-Williams and Howard-Williams 1978; Godshalk and Wetzel 1978b).

The second stage involves relatively rapid microbial oxidation of the majority of plant litter. The length of this stage varies from 3 months to over a year in temperate lakes, depending on biochemical make-up of the plant litter and environmental conditions (Jewell 1971; Carpenter 1980; Boyd 1970, 1971; Godshalk and Wetzel 1978a).

The final stage of decomposition involves slow oxidation of the litter's more refractory material. The rate of decomposition asymptotically approaches zero (Godshalk and Wetzel 1978a), making the time requirement indefinite. The percentage of plant litter falling into the refractory category has been reported at from 18.5 to 24 (Jewell 1971; Carpenter 1980), although in some cases plant litter decomposition is complete within a year inferring a small refractory portion (Howard-Williams and Davies 1979).

Mathematical models describing plant litter decomposition

Mathematical expressions have been used to describe the rate of plant litter decomposition. The simplest assumption is that the weight loss is a constant through time giving the linear model,

$$W_t = W_o - Ct \quad . \quad . \quad . \quad . \quad . \quad . \quad (1)$$

where

W_t is weight at time t
W_o is weight at time zero
C is a constant, describing the weight loss per unit time
t is time

The decomposition of Phragmites communis and Typha angustifolia in the Norfolk Broad closely followed a linear model for 300 days following an initial leaching period during which the rate of weight loss was high (10-20 percent in 30 days) (Mason and Bryant 1975). However, in most cases weight loss of plant litter has been approximately proportional to the quantity of plant litter remaining, rather than a constant through time. Therefore, a simple exponential model is often used to describe litter weight loss through time (Jewell 1971; Hodkinson 1975; Carpenter and Adams 1979; Sudo et al. 1978; Howard-Williams and Davies 1979). The equations describing such a model are:

$$dW/dt = -KW \quad . \quad . \quad . \quad . \quad . \quad . \quad (2)$$

where

W is the plant litter weight

t is time
K is a coefficient defining the proportion of litter decomposed per unit time

Integrating Equation 2 from time zero to t yields:

$$W = W_o e^{-Kt} \quad . \quad . \quad . \quad . \quad . \quad . \quad (3)$$

where W_o is the weight at time zero and all other terms have been defined.

Saunders (1975) points out that decay rates should be second order reactions, depending upon the amount of plant litter substrate and decomposer enzyme concentrations, rather than first order as assumed by the simple exponential model. However, litter decomposition usually occurs in dense weed beds where enzyme concentrations are very high so the second order equation reduces to first order (Saunders 1975).

Although the simple exponential model has been used with good success to describe litter decomposition rates, the assumed constant decay rate would only be true if the material being decomposed was homogeneous. Aquatic plants are not homogeneous (Adams et al. 1973; Boyd 1968, 1969), and a constant decay rate through time should not be expected. Indeed, the simple exponential model often underestimates the early rate of plant decay (that stage of rapid decomposition of labile plant components and abiotic leaching) and overestimates decay rates later in the decomposition cycle when refractory material dominates the litter (Godshalk 1977; Godshalk and Wetzel 1978a; Carpenter 1980).

Several approaches have been used to remedy the problem associated with the simple exponential model. For example, several investigators have circumvented the problem of representing the slowly decomposing refractory portions of plant litter by assigning a certain percentage of the total plant mass to the refractory portion and not considering that percentage in the simple exponential model (Jewell 1971; Sudo et al. 1978). The describing equations are

$$dW/dt = -K(W - fW_o) \quad . \quad . \quad . \quad (4)$$

Integrating from time zero to "t" yields:

$$W = (W_o - fW_o)e^{-Kt} + fW_o \quad . \quad . \quad (5)$$

where f is the refractory proportion and all other terms have previously been defined. Using this approach, the average value of "f" is approximately 25 percent (Jewell 1971). In a large model constructed to predict nutrient input to Lake Wingra from decomposing plants, Carpenter (1980) used the simple exponential model (Equation 3) to describe plant decay but removed the litter from consideration when the percent remaining fell below 18.5, the same principle employed in deriving Equation 5.

Considering a portion of the plant litter as nonbiodegradable is unsatisfactory, because most of it will eventually degrade, although slowly. The refractory material has some of the same ecological significances as the rest of the plant litter (e.g., dissolved oxygen consumption, nutrient regeneration, and energy supply for heterotrophs) but its effect is less in magnitude and longer lasting (see Reichle et al. 1975; Rich and Wetzel 1978). An additional problem with the above approach is that the first portion (about 75 percent) of the plant material is still assumed to be homogeneous and follows a simple exponential model.

A double exponential model (in which the first equation describes the more rapidly decomposing material and the second describes refractory material) has also been used (Bunnell et al. 1977). Recorded data often fit well to the double exponential model, but the use of two coefficients, instead of any other number, is arbitrary and biologically unfounded

(Bunnell et al. 1977). Minderman (1968) improved on the double exponential approach by estimating a decay coefficient for each important plant constituent (i.e., lignin, cellulose, sugars, hemicellulose, phenols, and waxes) and summing the results over the time period of decay. Since each constituent is a relatively homogeneous material, the basic assumption implied by the simple exponential model (i.e., an even decay rate through time) is not violated. By using chemical-specific utilization rates, Minderman (1968) found he could predict plant litter decay rates well in cases where the simple exponential model failed. A problem with Minderman's (1968) approach is that many detailed and difficult chemical analyses are needed on the plant litter. Another problem is that masking occurs when a relatively labile material is surrounded by a thin layer of refractory material impermeable to the decomposers, and results in a slower decomposition rate than predicted for the labile material.

Bunnell et al. (1977) used Minderman's concept to predict litter weight loss, but added a dimension which made the model more applicable to field decomposition. They defined the rate of litter loss not only as a function of chemical-specific utilization rates, but also a function of how these separate rates were affected by temperature and moisture content.

Godshalk (1977) developed a decomposition model which uses the simple exponential decay equation but has the added dimension of a decay coefficient which can also decrease exponentially through time. The following equations describe Godshalk's (1977) decay coefficient as a function of time:

$$dK/dt = -aK \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (6)$$

Integrating from time zero to "t" yields

$$K_t = K_o e^{-at} \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (7)$$

where

K_t is the decay coefficient at time "t"
K_o is the decay coefficient at time zero
a is a constant term which describes the reduction of K per unit time
t is time

Substituting Equation 7 into Equation 2 and integrating from zero to t:

$$W_t = W_o e^{K_o/a(e^{-at} - 1)} \quad . \quad . \quad . \quad . \quad (8)$$

All of the terms have been defined previously. Godshalk (1977) uses the simple exponential model, which has proven valuable in describing decomposition of other studies, in a way that does not make the assumption of a homogeneous material. Since the decay coefficient can change through time, the early period of rapid weight loss and the later period of decomposition due to refractory material can both be described equally well. Two coefficients describe the rate of decomposition through the entire decomposition cycle. A summary of this model is presented in Figure 1.

In summary, Minderman's (1968) and Godshalk's (1977) approaches are theoretically sound. Both approaches build on the simple exponential model without making a faulty assumption concerning the homogeneity of plant litter. However, the two approaches have different applications. Minderman's (1968) approach is much more cumbersome, but lends itself to accurately predicting plant litter decay rates if the composition of the plant is known. Godshalk's (1977) model is more easily used (the only data required are the proportions of plant remaining through time), but its two coefficients represent a multitude of environmental and tissue-specific variables which are not easily separable from one another. Thus its predictive value is limited,

but the model is easily and accurately used to compare decomposition of one treatment to another in decomposition studies.

Uses and Limitations of Microcosms in Ecological Research

In general, a microcosm is a simplified enclosed system designed to represent a portion of a natural ecosystem. Microcosms are designed to allow control over the biological, chemical, and physical properties of the system. Design decisions are usually based on tradeoffs between creating a system which allows direct measurement of system properties to meet research goals and preserving characteristics of the natural system being represented by the microcosm important to the processes being studied. Microcosms have ranged from very simple systems, e.g., laboratory flasks filled with artificial medium and a few selected algal species (e.g., Taub and Crow 1980; Cheslak 1981) to large, complex in situ enclosures encompassing total biological, chemical, and physical environments (e.g., de Noyelles et al. 1980; Elmgren et al. 1980). Objectives pursued through other microcosm studies have included: 1) assessment of environmental impacts of contaminants, toxicants, heavy metals, and potential carcinogens on aquatic systems (e.g., Porcella et al. 1975; Medine and Porcella 1981; Harte et al. 1980; Bowling et al. 1980; Dickson et al. 1982), 2) ecosystem modeling and analysis (e.g., Hill and Wiegert 1980; Heath 1980), 3) studying ecosystem functions such as photosynthesis, decomposition, and nutrient cycling

$$W_t = W_o e^{(K_o/a)(e^{-at} - 1)} \quad \ldots\ldots\ldots\ldots\ldots\ldots \quad (8)$$

t is the variable time (days)

W_t is the litter weight remaining at time t

W_o is the initial plant litter weight (one, if data are presented as proportions)

K_o is a parameter describing the initial rate of litter decomposition ($days^{-1}$)

a is a parameter which defines the rate at which the decomposition rate changes through time ($days^{-1}$)

Figure 1. Plant litter decomposition model developed by Godshalk (1977).

(Beyers 1963; Cooke 1967; Werner 1979), and 4) examining water-sediment interaction (Whittaker 1961; Porcella et al. 1975; Medine and Porcella 1981; Cowan et al. 1976; Stube et al. 1976; Dickson et al. 1982).

For many purposes, the microcosm approach offers substantial advantages. Microcosms can be designed to be of a size and complexity which permits sufficient replicability for reliable statistical analysis of the problem at hand. The control exercised over the experimental units allows system manipulation without invoking unreasonable expense, or natural ecosystem damage. Direct measurements can be made without the complexity of confounding factors present in natural systems. Thus, causal relationships are more easily identified in the simplistic system of a typical microcosm study. Finally, the use of microcosms in ecological or environmental research allows for rapid assessment of the problem being studied. In this regard, microcosms are a valuable tool in formulating hypotheses and/or identifying productive areas of study that can then be pursued by field research. In summary, microcosms offer advantages over field studies for the following considerations; time, scale of experiment, replication, economic feasibility, parameter measurement feasibility, and control over the experimental environment (Leffler 1980).

There are also problems and limitations associated with the use of microcosms for studying complex environmental problems. The use of microcosms requires an extrapolation to "real world" systems that must be tempered by an understanding of the assumptions made in designing the simplified system (Giesy and Odum 1980). King (1980) stresses that factors important to a process can often be readily identified in microcosm studies, but rate-effects of the factors on the process and the extent of these effects are often quite different in a simplified, artificial microcosm system than in a natural system. Another limitation to the microcosm approach lies in the danger of excluding components which might affect the process being investigated. For example, physical energy used for mixing in microcosms is considered to be important to the physiology of plankton in aquatic systems (Nixon et al. 1979, 1980).

In summary, results of microcosm studies must be interpreted with caution, and microcosms must only be used to study properties common to both the microcosm and the "real world" ecosystem. This statement, however, is not to diminish the utility of microcosms for studying a large set of environmental problems. Microcosm studies can provide direct and productive ways of examining interactive processes limiting and/or controlling biological activity in aquatic systems. Microcosms are a very effective tool for tracing the effects of contaminants, of all types, on the overall structure and function of biological communities. Much of the work accomplished in this area would have been impossible without the microcosm technique.

PART I

MICROCOSM STUDY TO ASSESS CRUDE OILS IMPACTS ON AN ENTIRE ECOSYSTEM

MATERIALS AND METHODS

The major objective of this portion of the research was to determine impacts of two crude oils on a total laboratory freshwater ecosystem simulating actual lakes. Three-phase microcosms were used to contain the experimental ecosystems and crude oil was added after a complex biological community had developed. Bioassay tests were performed prior to microcosm experiments to determine 1) the degree of toxicity the crude oils being used had on a test photoautotroph and 2) to help assure oil dosages so high that they would totally inhibit photoautotrophic growth in the microcosms.

Study Sites

Two lakes potentially threatened by petroleum spills by energy development within the overthrust belt of the Rocky Mountain West were chosen as study sites for this research. Bear Lake (BL) is located on the Utah-Idaho border in the Wasatch Mountain Range and New Fork Lake (NFL) is in the Wind River Mountain Range of Western Wyoming. Bear Lake is within a limestone drainage and can be considered a hard water lake. Conversely, New Fork Lake is located in a granitic watershed and contains soft water. Thus the lakes have very different aqueous chemistries. Physical and chemical properties of the lakes are listed in Table 1.

Bioassay Experiment

Bioassay experiments were performed with Selenastrum capricornutum as the test algal species to assess the effect of several concentrations of South Louisiana Crude (SLC) and Wyoming Crude (WC) on algal growth. SLC was chosen as a test oil because it is a standard American Petroleum Institute crude oil often used in marine pollution studies and as such would provide a basis for comparing this research with marine studies. WC is a local oil that provided insight on effects that could be

Table 1. Physical and chemical properties of the two experimental lakes.

Parameter	Bear Lake	New Fork Lake
Area (hectares)	28,500	440
Maximum Depth (m)	61	43
Total Alkalinity (mg/l as $CaCO_3$)	265[a]	18
Total Hardness (mg/l as $CaCO_3$)	320	20
Calcium (mg/l as Ca^{++})	69	5.4
Magnesium (mg/l as Mg^{++})	41	1.6
Sodium (mg/l)	39	-
Potassium (mg/l)	3	3
Chloride (mg/l)	46	1.5
Sulfate (mg/l)	16	5.8
Total Phosphorus (µg/l)	7	8
Total Inorganic Nitrogen (µg/l)	49	81

[a]Water chemistry values are average values taken from eight sites in BL in October 1979 and one site in NFL in November 1979. Analytical techniques are given in Appendix A.

expected from an accidental spill at a drilling or transport site in the region. SLC was obtained from Dr. J. M. Anderson of Texas A & M University. WC was provided by Phillips Oil Company, Salt Lake City, Utah, its origin was the overthrust belt of Western Wyoming. Bioassay procedures as prescribed by Miller et al. (1978) were followed, with the exception that media simulating Bear and New Fork Lakes water chemistries were used rather than the recommended synthetic algal nutrient medium. Critical nutrient (N and P) levels in the media were as recommended.

Two modes of oil injection and four oil concentrations were used for each oil type and each of the experimental lakes. Three replicates represented each treatment. The two modes of injection were direct application of oil and oil in suspension. Direct application involved placing the prescribed quantity of oil directly on the water surface of individual bioassay flasks. The suspension treatments were initiated by shaking a mixture of medium with a prescribed quantity of oil for 24 hours at 100 rpm, allowing the mixture to separate, and removing the aqueous portion for the bioassay experiment. Table 2 gives the oil concentrations for each injection mode and each crude oil. Those concentrations were chosen to show crude oils' effects at several concentrations too low for complete growth inhibition on the alga. The oil concentration at which complete growth inhibition occurred was determined in preliminary tests.

Parameters tested were the alga's maximum growth rate (μ) and its maximum standing crop ($\hat{x}$). μ is defined as

$$\mu = \frac{\ln \frac{x_2}{x_1}}{t_2 - t_1} \quad \ldots\ldots\ldots (9)$$

Table 2. Concentrations of oil injected into Bear and New Fork Lake simulated media to establish treatments for bioassay experiments.

Injection Mode	Oil Type	
	South Louisiana Crude	Wyoming Crude
Direct	0 ml oil/ℓ medium	0 ml oil/ℓ medium
	0.08 ml oil/ℓ medium	0.08 ml oil/ℓ medium
	0.56 ml oil/ℓ medium	0.32 ml oil/ℓ medium
	2.8 ml oil/ℓ medium	0.56 ml oil/ℓ medium
Suspended	0 ml oil/ℓ medium	0 ml oil/ℓ medium
	1.0 ml oil/ℓ medium	1.0 ml oil/ℓ medium
	10.0 ml oil/ℓ medium	3.0 ml oil/ℓ medium
	20.0 ml oil/ℓ medium	6.0 ml oil/ℓ medium

where

x_2 is biomass at time t2
x_1 is biomass at time t1

x is defined as the highest biomass which occurs after which a 5 percent (or greater) per day increase in biomass does not take place (Cleave 1979; USEPA 1971). Duncan's multiple range test was used in statistical analyses of the data as described by Cleave (1979).

Microcosm Description

A schematic of the microcosm used for this investigation is presented in Figure 2. Gaseous, aqueous, and sediment phases were included in the microcosm. The microcosms were sealed systems; the gaseous phase had an interface with a 2.5 percent H_2SO_4 solution containing methyl red dye (Porcella et al. 1975). The acid solution precluded gaseous exchange across the interface, and the dye clearly defined the position of the interface in the buret.

All interior surfaces of the microcosms were either glass or teflon which eliminated the possibility of organic contamination from within the microcosm itself. A water driven magnetic stirrer continuously mixed the aqueous phase to facilitate gaseous exchange across the gaseous-aqueous phase boundary and precluded stratification within the aqueous phase. Additional information on this microcosm system are found in Dickson et al. (1982) and on similar systems in Porcella et al. (1975), Cowan et al. (1976), Stube et al. (1976), and Medine and Porcella (1981).

External conditions of microcosms

Microcosms were exposed to either continual darkness or a 16 hour light-8 hour dark diurnal cycle throughout the experiment. Darkness was assured by enclosing the microcosms in a cabinet sealed against light. Light was provided to the diurnal microcosms by Optima 50 fluorescent bulbs (Duro Test Corp.) connected to an automatic timer. Light intensity on the microcosms ranged from 510 to 590 μ Einsteins/m^2 s. The diurnal condition would include biota representative of the natural ecosystem. In contrast, the dark condition was more simplistic, only decomposers and chemoautotrophs would be present. Data

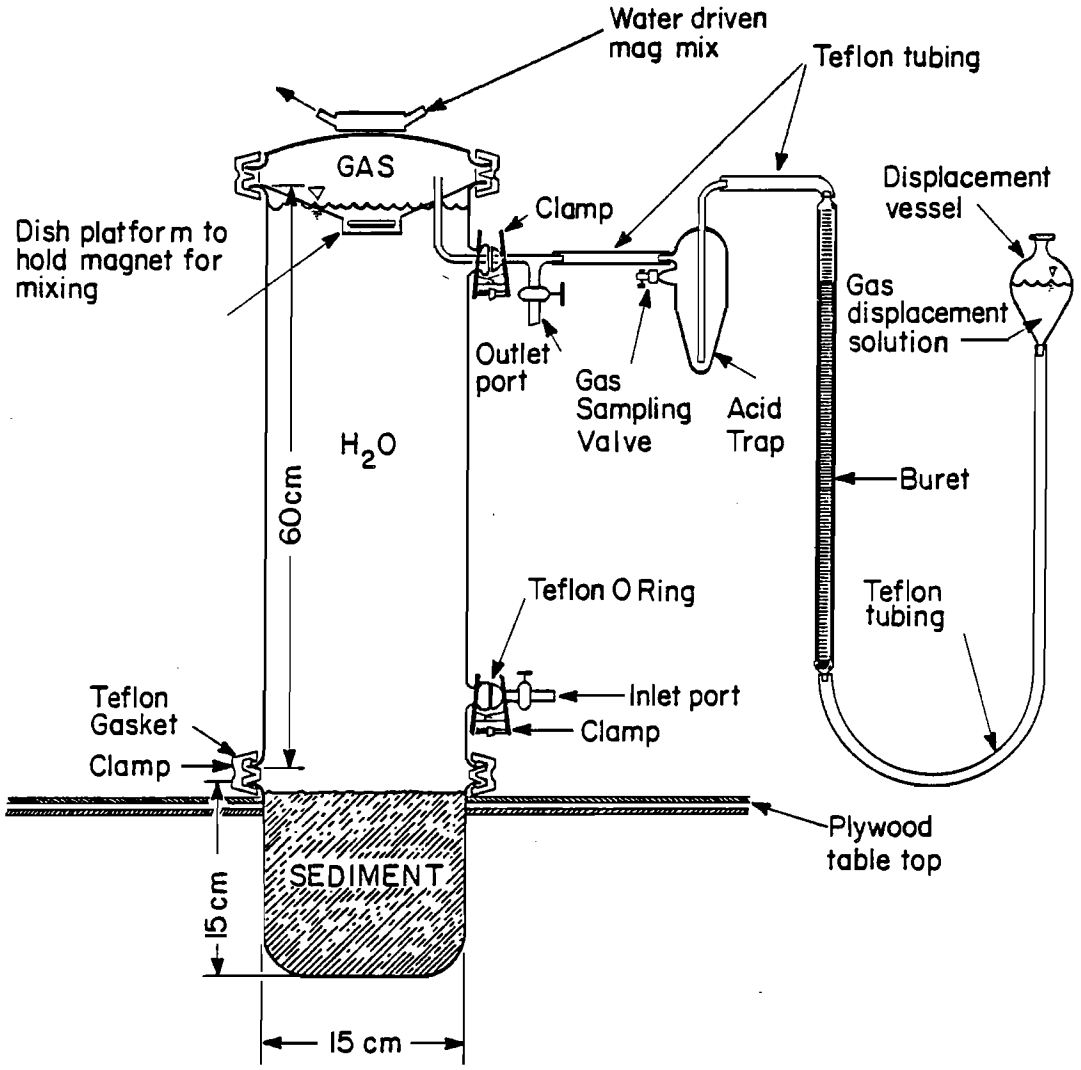


Figure 2. Schematic of microcosm (from Dickson et al. 1982).

analyses of the latter would be confounded by fewer factors, and thus more certain, and could be used to help interpret results from the former.

The microcosm experiments were conducted in a temperature controlled room at the Utah Water Research Laboratory. Room temperature ranged from about 19 to 23°C during the New Fork Lake experiment and from 20 to 23°C during the Bear Lake experiment. These temperatures correspond to maximum temperature in the lakes.

Experimental design

The microcosm experiments simulating Bear and New Fork Lakes were performed at different times, but the initial experimental designs were identical for the two lakes. Dark and diurnal light conditions were included. Three treatments were established for each light condition. 1) unoiled control microcosms, 2) microcosms exposed to South Louisiana Crude oil, and 3) those exposed to Wyoming Crude oil. Three replicates

were initially provided for all diurnal treatments and one for all dark treatments. The three treatments were randomly assigned to the various microcosms. An outline of the various treatment conditions for the experimental microcosms are presented in Table 3.

Treatments were initiated by injecting 3.74 ml of one of the oil types through the bottom inlet port of the prescribed microcosm using a long needled hypodermic syringe. Treatments were established on day 42 of the experiment and responses of the microcosm ecosystem were analyzed for the following 48 days. Thus, the overall duration of a microcosm experiment was 90 days. Day 42 was chosen as the time to initialize treatments because gas production/consumption had reached steady state conditions by that time. One microcosm for each diurnal treatment was dismantled during the New Fork experiment 20 days after treatment initiation to assess interim plant densities. However, all three replicates for each diurnal treatment were maintained throughout the entire 90 day Bear Lake experiment.

Set-up procedure for microcosm

Natural lake sediments were collected for the sediment phase of the microcosms from the upper 15 cm of sediment surface in the littoral region of each lake. Collection sites were the western shore of Bear Lake near Fish Haven, Idaho, and approximately 200 m east of the boat ramp on New Fork Lake's northern shore. Sediments were transported to the laboratory in 55 gal teflon lined drums and stored at 6°C until used.

The entire collected sediment mass was completely mixed before being used in the microcosm study. The sediment phase was filled by weighing sediment aliquots of approximately 400 g and

Table 3. Treatment assignments of various microcosms.

Microcosm Number	Light Condition	Bear Lake Treatment	New Fork Lake Treatment
1	Diurnal (16 hrs light-8 hrs dark)	S. La. Crude[a]	S. La. Crude
2	"	Control	Control
3	"	Wyo. Crude[b]	S. La. Crude
4	"	S. La. Crude	Control[c]
5	"	Wyo. Crude	Wyo. Crude
6	"	Control	Control
7	"	Control	S. La. Crude[c]
8	"	S. La. Crude	Wyo. Crude[c]
9	"	Wyo. Crude	Wyo. Crude
10	Dark	S. La. Crude	S. La. Crude
11	"	Wyo. Crude	Wyo. Crude
12	"	Control	Control

[a]South Louisiana Crude.
[b]Wyoming Crude
[c]These microcosms were dismantled for interim plant analyses 20 days after treatment initiation.

placing these into individual microcosms until a final sediment weight of approximately 4.5 kilograms was achieved in each microcosm. Successive layers were placed in each microcosm before the next layer was placed in any microcosm to improve sediment homogeneity among microcosms.

The aqueous phase of each microcosm was composed of an artificial medium which simulated the macrochemistry of the study lake. Chemical compositions of stock solutions and final medium for Bear and New Fork Lakes experiments are presented in Tables 4 and 5, respectively. Concentrations of various constituents in the final water for both lakes are in Table 6. The volume of medium initially added to the individual microcosms was measured and recorded. In addition to the artificial medium, 1 liter of fresh lake water was added to each aqueous phase to provide an inoculum of the lake's organisms. After a microcosm received the required quantity of aqueous medium, it was maintained in the dark long enough to allow suspended sediments to settle (2 days for New Fork Lake and 1 day for Bear Lake). Two liters from the aqueous phase of each microcosm were then collected, mixed with medium collected from the other microcosms, and 2 liters of the mixture were redistributed to all microcosms. This cross-inoculation procedure was performed on two successive days to improve the homogeneity of the aqueous chemistry and biological species over all microcosms. Finally, the microcosms were sealed from the atmosphere, the light cycle was established in the diurnal microcosms, and the experiment began. The initial composition of the gas phase was that of atmospheric air. Initial physical conditions of the microcosms are listed in Table 7.

Table 4. Simulated Bear Lake medium.

Compound		Quantity† in Stock Solution (g/l)	Dilution Factor for Final Aqueous Medium	Final Concentration of Microcosm Medium (mg/l)
$NaHCO_3$	a*	14.2812	10 → 1000	142.8
$KHCO_3$	a	0.8010	10 → 1000	8.0
$MgCl_2$-$6H_2O$	b	15.5532	10 → 1000	155.5
$MgSO_4$-$7H_2O$	b	5.0529	10 → 1000	50.5
$Ca(OH)_2$	**	0.0878	No dilution	87.8
$MgCO_3$-$Mg(OH)_2$-nH_2O**		0.0394	No dilution	39.4
$NaNO_3$	c	0.4709	1 → 1000	0.4709
KH_2PO_4	c	0.0352	1 → 1000	0.0352

†Weighed to 0.0001 g.

*Compounds with common letters were combined in a stock solution.

**Stock solutions were not made for these compounds. Bubbling with CO_2 was required to dissolve the compounds into the aqueous media.

Table 5. Simulated New Fork Lake medium.

Compound		Quantity† in Stock Solution (g/l)	Dilution Factor for Final Aqueous Medium	Final Concentration of Microcosm Medium (mg/l)
$CaCl_2$	a*	0.2491	10 → 1000	2.5
$MgSO_4 \cdot 7H_2O$	a	1.3558	10 → 1000	13.6
$CaSO_4$	a	0.1634	10 → 1000	1.6
$NaHCO_3$	b	0.3655	10 → 1000	3.7
$KHCO_3$	b	0.8010	10 → 1000	8.0
$Ca(OH)_2$	**	0.0746	100 → 1000	7.5
$NaNO_3$	c	0.4709	1 → 1000	0.4709
KH_2PO_4	c	0.0352	1 → 1000	0.0352

†Weighed to 0.0001 g.

*Compounds with common letters were combined in a stock solution.

**Bubbling with CO_2 was necessary to dissolve this compound into its stock solution.

Table 6. Final concentrations of various constituents in Bear and New Fork Lakes' media (standard deviation in parentheses).

Parameter	Bear Lake Aqueous Medium	New Fork Lake Aqueous Medium
Ca (mg/l)[a]	47.49	5.41
Mg (mg/l)[a]	33.54	1.33
Na (mg/l)[a]	39.08	0.99
K (mg/l)[a]	3.13	3.12
Cl (mg/l)[a]	54.24	1.62
$SO_4^=$ (mg/l)[a]	19.69	6.44
P (µg/l)[a]	8.01	8.01
N (µg/l)[a]	77.60	77.60
Alk (mg/l as $CaCO_3$)[b]	251.9 (10.1)	19.81
Total Hardness (mg/l as $CaCO_3$)[b]	253.7 (8.3)	25.7
pH[b]	8.2	7.0-7.7

[a]Calculated based on composition of medium.

[b]Measured quantities.

Table 7. Initial physical conditions of microcosms.

Microcosm Number	Bear Lake Study			New Fork Lake Study		
	Sediment Weight (g)	Aqueous Phase Volume (ℓ)	Gaseous Phase Volume (ℓ)	Sediment Weight (g)	Aqueous Phase Volume (ℓ)	Gaseous Phase Volume (ℓ)
1	4447	10.35	0.957	4265	10.33	0.881
2	4497	10.28	0.982	4830	10.36	0.881
3	4247	10.27	0.992	4330	10.56	0.892
4	4307	10.37	0.960	4720	10.50	0.884
5	4217	10.27	0.986	4520	10.42	0.891
6	4247	10.20	0.962	4600	10.38	0.894
7	4247	10.28	0.960	4620	10.43	0.923
8	4167	10.25	0.989	4555	10.43	0.914
9	4027	10.27	0.990	4385	10.52	0.905
10	5245	10.25	0.992	4730	10.36	0.902
11	4187	10.25	0.989	4600	10.36	0.897
12	4247	10.38	0.991	4685	10.38	0.897
Mean	4340	10.29	0.979	4570	10.42	0.897
Standard Deviation	310	0.05	0.015	171	0.07	0.013
Range	4027-5245	10.20-10.38	0.957-0.992	4265-4830	10.33-10.56	0.881-0.923

Experimental Procedures and Protocol

Microcosm maintenance

The microcosms were maintained as semi-continuous cultures by exchanging approximately 1 liter of fresh medium for a liter of each microcosm's aqueous phase every other day. The average water residence time was thus from 20 to 21 days. Before being added to the microcosm, the fresh medium was chilled to 4-5°C below the temperature of the microcosms. The medium was chilled to preclude immediate mixing with the microcosm's aqueous phase which might

lead to loss of the fresh medium during the exchange procedure (Porcella et al. 1975). During the exchange, fresh medium was added to the microcosm's lower inlet port while a liter of the microcosm's aqueous phase was being removed from the upper outlet port. The gas level in the manometer was read before each medium exchange began, and it was adjusted to its original level after the exchange procedure to assure that equal volumes of medium were added to, and removed from, the microcosms. The exact volume of medium exchange was then measured and recorded.

Additional measurements were made during the medium exchange procedure to enable a determination of the net production or consumption of gas since the last medium exchange. These measurements included barometric pressure, room temperature, and effluent aqueous temperature. A computer program (Micro-4) corrected gas volumes to standard conditions; differences of gas volumes on successive dates were net gas production or consumption (Appendix B). A complete list of parameters measured on medium exchange dates, and their purposes, is presented in Table 8.

Table 8. Parameters measured on medium exchange dates.

Parameter Measured	Rationale
Room Temperature	Early detection of problems associated with temperature change.
Temperature of Fresh Medium	Assure temperature was low enough to preclude immediate mixing with microcosm aqueous phase. Necessary for calculations to determine dissolved gases entering the microcosms.
Temperature of Effluent Aqueous Phase	Necessary to determine gas solubilities and therefore removal from microcosms. Correct volume of overlying gaseous phase to standard temperature based on its volume at the temperature of the microcosms aqueous phase.
pH of Fresh Medium	Assure pH was in proper range to avoid shock to organisms in microcosm.
Volume of Effluent Aqueous Phase	Used for mass balance calculations of microcosms constituents (e.g. nutrients and dissolved gases).
Initial Manometer Reading	Calculate net change of gases from previous date.
Final Manometer Reading	Initial point for determining net change of gases for next date. Determine if more or less medium entered the microcosm than aqueous phase removed.
Barometric Pressure	Correct gas volume to standard pressure.

Sampling parameters

Eleven water chemistry parameters were measured every 10 days for the microcosms. The parameters included: pH, alkalinity, total hardness, calcium, dissolved oxygen, total organic carbon, nitrate, nitrite, ammonia, total phosphorus, and orthophosphate. The measurement techniques are listed in Appendix A.

Gas samples were collected every 10 days through gas sampling valves (Figure 2). The mole fractions of nitrogen, oxygen, carbon dioxide, and methane were estimated in triplicate for each microcosm. A Hewlett-Packard Model 5750 gas chromatograph was used under the following operating conditions:

Columns - 1.8 m x 0.32 cm o.d. stainless-steel containing 60-80 Molecular Sieve 5A (for O_2, N_2, CH_4)
- 1.8 m x 0.32 cm o.d. stainless-steel containing 120 Poropak S (for CO_2)

Carrier Gas - Helium

Flow Rates - Carrier gas - 35 ml/min

Temperatures - Column - 60-70°C
Detector - 180°C
Injection port-120°C

Calibration was performed using a gas standard of known composition.

Sediment was analyzed at the beginning and end of the experiment for total phosphorus, nitrate, nitrite, ammonia, and organic matter content. Initially, subsamples were pooled and analyzed collectively. At the experiment's termination, sediment cores were divided into four depths (surface-2 cm, 2 cm-4 cm, 4 cm-6 cm, greater than 6 cm) and analyzed separately. Techniques used for these analyses appear in Appendix A.

Additional analyses

Several additional analyses were periodically performed on the aqueous phase of Bear Lake microcosms. These included bacterial enumeration, planktonic invertebrate enumeration, and relative fluorescence of planktonic algae. The techniques used are presented in Appendix A.

Analyses at experiment's termination

Biomass analyses were performed on the final day of each experiment at three sites in each microcosm; namely the water column, glass surface, and sediment surface. Aliquots of aqueous medium were filtered through preweighed GF/C glass fiber filters to measure planktonic biomass. All glass surfaces were scraped clean using a rubber spatula; the collected material was suspended in tap water and then filtered through preweighed glass fiber filters to assess periphytic biomass. Sediment surface macrophytes and filamentous algae were separated from sediment particles to measure biomass in that zone. Samples from all zones were dried at 60°C for 48 hours, weighed to the nearest 0.1 mg, and then ashed at 550°C for 2 hours. Samples were reweighed and ash free dry weights of the biomass calculated.

Sediment samples were collected by inserting a 2.5 cm diameter glass tube vertically through the sediment profile. A small glass tube was inserted adjacent to the sampling tube to relieve negative pressure as the stoppered sampling tube was being withdrawn. Triplicate sediment samples were taken from each microcosm. The glass tube with the sediment profile was stoppered at both ends and frozen until analyses could be performed. Before sediment analyses were done, the frozen sediment was extracted from the glass tube and cut in the following sections: surface to 2 cm, 2-4 cm, 4-6 cm, greater than 6 cm.

Chemical analyses were performed on each section.

Oil from the water surface of oiled microcosms was collected on the final date and stored in glass bottles with teflon tops in a refrigerator for later GC/MS analyses.

A portion of the aqueous phase collected on the final day of the Bear Lake microcosm experiment was used to determine the growth response of Selenastrum capricornutum to the various treatments. Phosphorus and nitrogen were added to the medium to obtain two different nutrient concentration levels (50 µg/l P; 485 µg/l N and 100 µg/l P; 970 µg/l N). The procedures of Miller et al. (1978) for algal bioassay tests were used except that the medium was not sterilized and approximately 20 times the recommended cell concentration of S. capricornutum were added to each experimental flask at the onset of the experiment. (The medium was not sterilized to avoid denaturing the dissolved oil and the increased inoculum was used to give the algae a competitive advantage for nutrient assimilation over the existing decomposer organisms.) Relative fluorescence was determined six times during the next 10 days to assess population growth of the algae.

Data analysis

Mass balance analyses of the microcosm data were performed using a modified version of Program Micro (Porcella et al. 1975). That program was specifically written for microcosm data analysis, and the version used (Micro 4) is presented in Appendix B.

A split plot through time analysis of variance model was used to analyze those parameters measured at 10 day intervals (repeated measurements were performed on a single microcosm through time). Statistical analyses were accomplished using statistical packages and minitab on the Burroughs 6800 and Vax computers.

RESULTS

Bioassay

Effects of the direct addition of South Louisiana and Wyoming Crude oils on the growth of Selenastrum in the bioassay test are shown in Figure 3. Results of statistical analyses of these data for differences among doses are presented in Table 9. In general, both crude oils reduced the growth of the algae; and greater oil dosages increased the deleterious effects of a given oil. Direct injection of South Louisiana Crude led to statistically significant differences for μ and $\hat{x}$[1] between each oil concentration except the 0.08 and 0.56 ml oil/l dosages. Direct injection of Wyoming Crude led to significant differences except for parameter μ, between the no oil and 0.08 ml oil dosages and the 0.08 and 0.56 ml dosages (Table 9).

Addition of suspended oil to the Bear Lake medium generally caused differences in $\hat{x}$ but not μ (Figure 4 and Table 9). Furthermore, the initial concentration of oils had little effect on either $\hat{x}$ or μ. Apparently, approximately equal concentrations of deleterious hydrocarbons dissolved in the medium and exerted their influence on the algal population regardless of the initial dose of oil added.

Effects of the various oil concentrations added directly to the New Fork medium are shown in Figure 5. The lowest oil concentration (0.08 ml oil/l) was not significantly different from the control for μ or $\hat{x}$ for either crude oil type (Table 10). However, the medium and highest oil additions reduced both growth parameters from control values; there were also significant differences for μ and $\hat{x}$ between these two highest dosages.

As with Bear Lake medium, a lesser deleterious effect resulted when crude oils were added in suspension, rather than directly, to New Fork medium (Figure 6 and Table 10). Significant differences of μ and $\hat{x}$ existed only between controls (no oil) and the two highest oil concentrations.

Different dosages were used for the oils because Wyoming Crude had greater short term deleterious effects on algal growth than did South Louisiana Crude (e.g., compare 0.56 ml oil/l dosages for directly added oil). Dose concentrations of the two oils were selected which would not completely inhibit growth, to investigate a range of growth responses.

Maximum standing crop of algal biomass was approximately twice as great in New Fork medium as in the Bear Lake medium even though initial levels of critical nutrients (N and P) were the same. High pH values (up to 9.4) occurred shortly after the experiments began. Precipitation of calcium carbonate was observed in the Bear Lake experiment due to the medium's high alkalinity, but not in the New Fork experiment which had a medium with very low alkalinity. Coprecipitation of phosphorus in the Bear Lake medium (Rupp 1981) very likely lowered concentrations of that growth limiting nutrient in Bear Lake bioassay tests.

[1] $\hat{x}$ is alga's maximum standing crop and μ is its maximum growth rate.

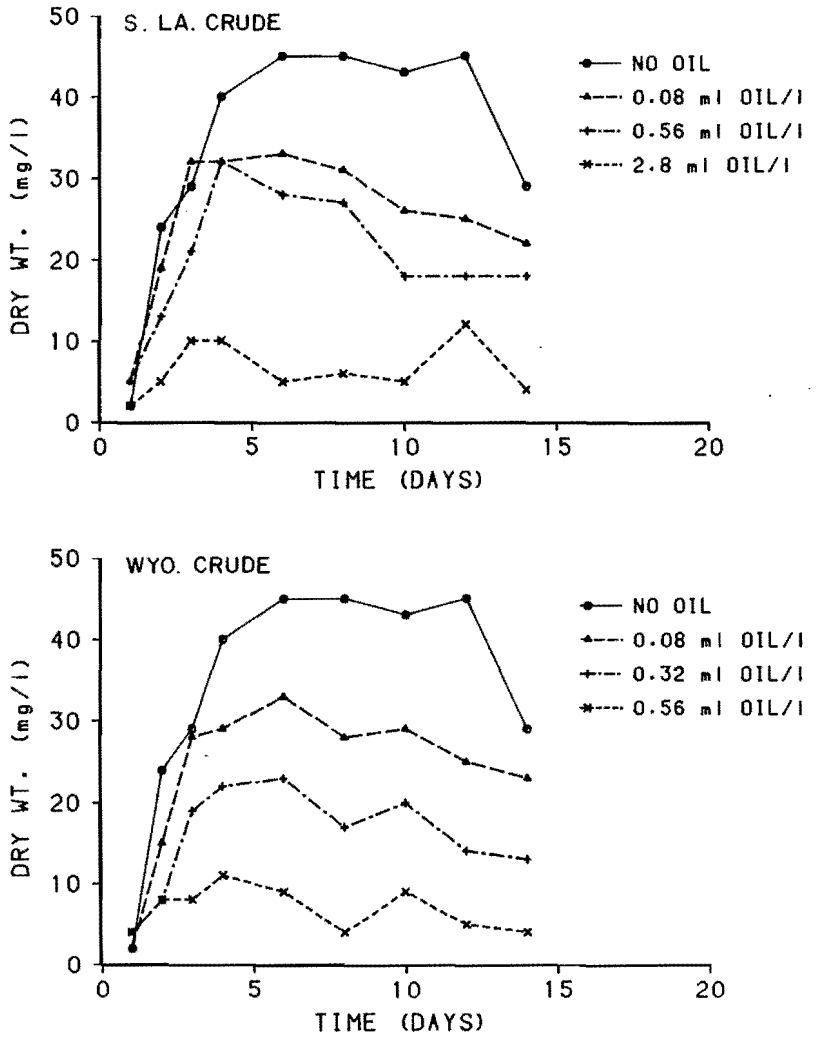


Figure 3. Comparisons of Selenastrum growth in Bear Lake medium with various concentrations of directly added crude oils.

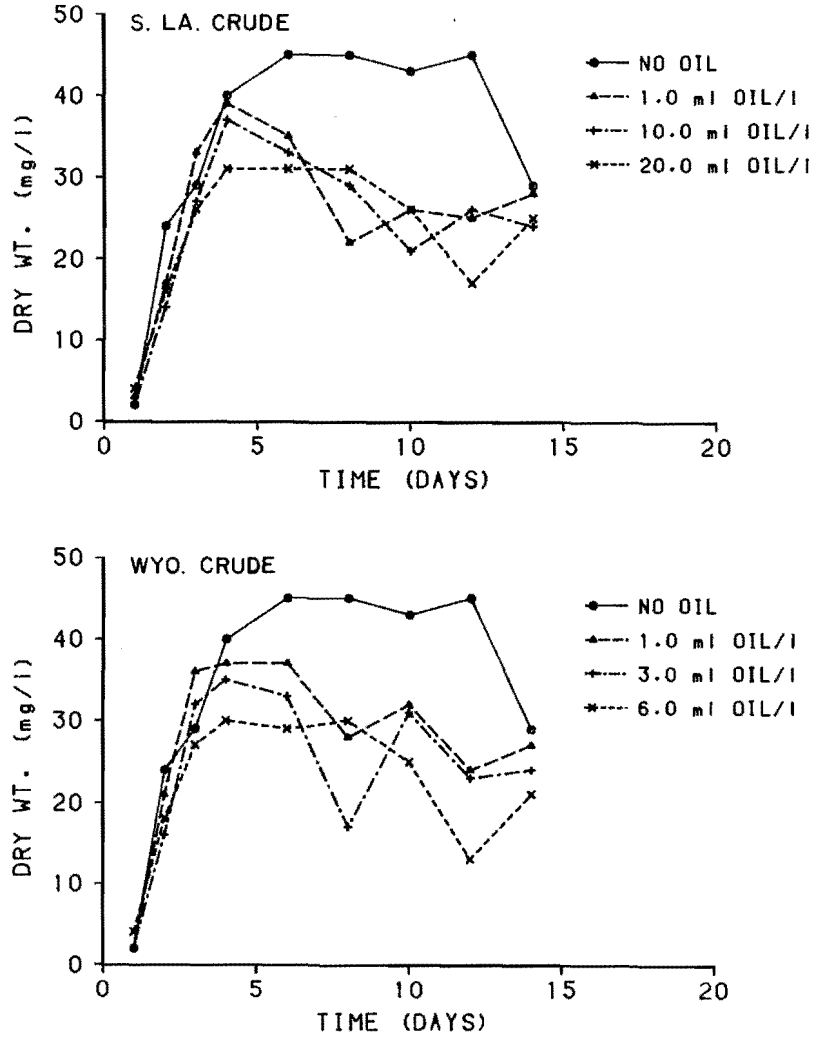


Figure 4. Comparisons of Selenastrum growth in Bear Lake medium with various concentrations of crude oil added in suspension.

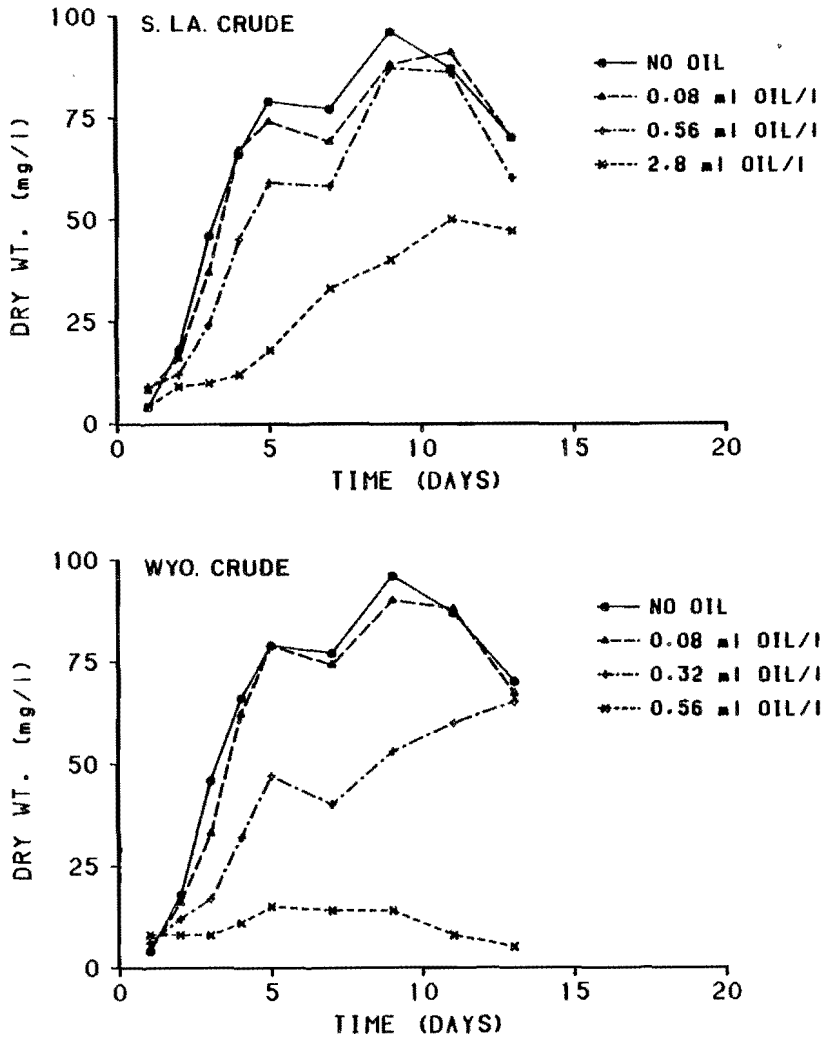


Figure 5. Comparisons of Selenastrum growth in New Fork Lake medium with various concentrations of directly added crude oils.

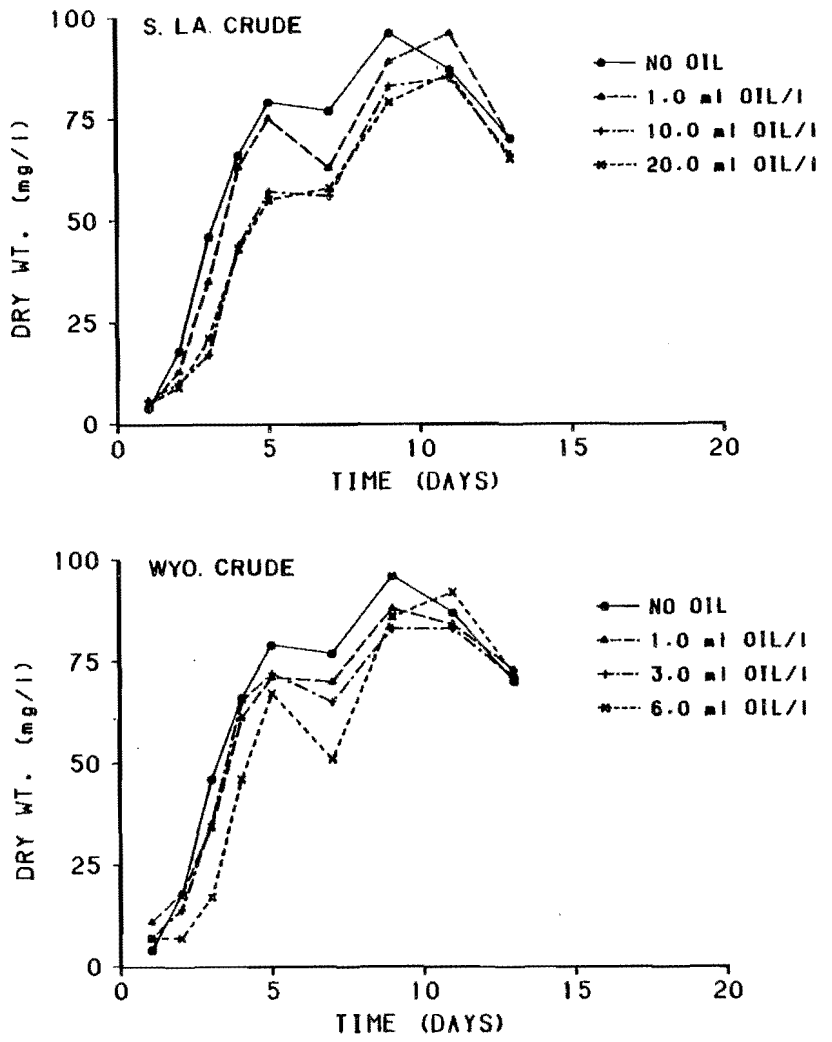


Figure 6. Comparisons of Selenastrum growth in New Fork Lake medium with various concentrations of crude oil added in suspension.

One reason for conducting this set of bioassay experiments was to determine an oil concentration to be added to microcosms which would not totally inhibit the growth of pelagic algae. Based on the bioassay experimentation, 0.32 ml of oil per liter of microcosm aqueous phase was ultimately selected as the desired dosage. That dosage resulted in 33 to 90 percent reductions in the S. capricornutum standing crop, considering bioassay results for both lakes and oil types (the percent reduction value for Bear Lake bioassays was obtained by linear interpolation between existing oil dosages).

Table 9. Bioassay results for two oils added in four concentrations to Bear Lake medium.

	Maximum Growth Rate- μ (mg/l-d)	Maximum Standing Crop-$\hat{x}$ (mg/l)
S. La. Crude Direct Addition		
No oil	13.6 A[a]	44.3 A
0.08 ml oil/ℓ	11.8 B	26.2 B
0.56 ml oil/ℓ	11.5 B	20.4 B
2.80 ml oil/ℓ	4.6 C	6.8 C
Wyo. Crude Direct Addition		
No oil	13.6 A	44.3 A
0.08 ml oil/ℓ	11.1 A B	26.4 B
0.32 ml oil/ℓ	8.8 B	14.7 C
0.56 ml oil/ℓ	4.6 C	5.4 D
S. La. Crude in Suspension		
No oil	13.6 A	44.3 A
1.0 ml oil/ℓ	13.6 A	25.2 B
10.0 ml oil/ℓ	12.9 A	24.8 B
20.0 ml oil/ℓ	11.2 A	24.4 B
Wyo. Crude in Suspension		
No oil	13.6 A	44.3 A
1.0 ml oil/ℓ	13.6 A	27.5 B
3.0 ml oil/ℓ	13.4 A	23.5 C
6.0 ml oil/ℓ	13.2 A	22.3 C

[a]Different letters among treatments within an experimental condition (e.g. S. La. Crude direct addition) indicates statistically significant differences at P = 0.95. When letters for different oil concentrations are in the same column, the response to oil pollution at those concentrations are not significantly different.

Table 10. Bioassay results for two crude oils added in four concentrations to New Fork Lake medium.

	Maximum Growth Rate-μ (mg/l-d)	Maximum Standing Crop-$\hat{x}$ (mg/l)
S. La. Crude Direct Addition		
No oil	23.3 A[a]	84.7 A
0.08 ml oil/ℓ	21.7 A	80.6 A B
0.56 ml oil/ℓ	17.1 B	72.5 B
2.80 ml oil/ℓ	6.8 C	35 C
Wyo. Crude Direct Addition		
No oil	23.3 A	84.7 A
0.08 ml oil/ℓ	21.1 A	80.3 A
0.32 ml oil/ℓ	13.6 B	49.7 B
0.56 ml oil/ℓ	4.9 C	12.5 C
S. La. Crude in Suspension		
No oil	23.3 A	84.7 A
1.0 ml oil/ℓ	22.8 A	81.1 A
10.0 ml oil/ℓ	16.8 B	70.5 B
20.0 ml oil/ℓ	16.6 B	69.5 B
Wyo. Crude in Suspension		
No oil	23.3 A	84.7 A
1.0 ml oil/ℓ	21.2 A B	78.4 A B
3.0 ml oil/ℓ	19.8 B	75.8 B
6.0 ml oil/ℓ	19.2 B	73.8 B

[a]Different letters among treatments within an experimental condition (e.g. S. La. Crude direct addition) indicates statistically significant differences at P = 0.95. When letters for different oil concentrations are in the same column, the response to oil pollution at those concentrations are not significantly different.

Microcosms

Sediments

Initial nutrient content, organic matter content, and bulk density of sediments used for the microcosm experiments are presented in Table 11. Tables 12 and 13 contain values for the same parameters (except bulk density) for four depth ranges within a sediment profile following the microcosm experiments for Bear Lake (BL) and New Fork Lake (NFL), respectively. Parameter values for BL diurnal microcosms are means of three microcosms and those for NFL diurnal microcosms are means of two units. All values for dark treatments

Table 11. Initial values for various sediment parameters. The sediments reported were subsequently used in the microcosm studies. Means are listed with the standard deviation in parentheses.

Parameter	Lakes	
	Bear Lake	New Fork Lake
Total Phosphorus (µg/g dry sed. wt.)	281 (22)	309 (11)
Ammonia (µg/g wet sed. wt.)	0.202 (0.062)	0.227 (0.079)
Nitrate (µg/g wet sed. wt.)	0.83 (0.26)	0.76 (0.14)
Nitrite (µg/g wet sed. wt.)	0.018 (0.001)	0.020 (0.006)
Percent Organic Matter	1.13 (0.08)	1.39 (0.08)
Density (g/cm^3)	1.10 (0.03)	1.34 (0.07)

are based on a single microcosm. Table 14 contains the above mentioned parameters for NFL diurnal microcosms 20 days after oil addition.

Sediment total phosphorus concentrations exhibited no consistent trends either within a profile or between treatments in either microcosm study. The sediment phosphorus analysis employed was not precise enough to detect changes within the range which potentially occurred during the experiment (see Appendix C).

Ammonia concentrations consistently increased with depth into the sediment in both studies. Additionally, sediment ammonia concentrations were greater at all depths after the experiment than initially. However, there was no consistent difference between the controls and oiled treatments in terms of sediment ammonia concentrations.

Nitrate and nitrite concentrations were low and variable at all depths and for all treatments. No consistent patterns regarding treatment or sediment depth effects were apparent. Finally, organic content was relatively constant over time and regardless of sediment position or treatment.

Aqueous chemistry

The values of aqueous parameters measured at 10-day intervals are presented in this section. Results for several other parameters can be found in Appendix D. Values for light microcosms are means of three microcosms for BL and two for NFL. When differences between treatments are cited, the differences are statistically significant ($P = 0.95$) based on analysis of variance tests. Summaries of test results for all parameters can be found in Appendix D. Values for dark microcosms are from a

Table 12. Values at four depths of sediment parameters on the final day of the Bear Lake microcosm experiment. Values in parentheses are standard deviations.

Condition	Treatment	Depth	Total Phos (µg/g Dry Wt.)	NH_3-N (µg/g Wet Wt.)	NO_3-N (µg/g Wet Wt.)	NO_2-N (µg/g Wet Wt.)	Percent Organic Matter
Diurnal[a]	Control	Sur. - 2 cm	282 (62)	1.49 (0.25)	1.40 (0.18)	0.16 (0.07)	1.11 (0.03)
		2 cm - 4 cm	255 (52)	2.30 (0.50)	1.66 (0.26)	0.09 (0.06)	1.08 (0.08)
		4 cm - 6 cm	266 (44)	2.56 (0.34)	1.44 (0.17)	0.08 (0.05)	
		> 6 cm	264 (5)	2.73 (0.14)	1.32 (0.05)	0.15 (0.09)	
	S. La. Crude	Sur. - 2 cm	246 (18)	1.69 (0.61)	1.93 (0.10)	0.16 (0.09)	1.08 (0.05)
		2 cm - 4 cm	287 (33)	3.15 (0.41)	1.77 (0.40)	0.11 (0.05)	1.08 (0.05)
		4 cm - 6 cm	340 (88)	2.62 (0.10)	1.31 (0.37)	0.09 (0.06)	
		> 6 cm	266 (41)	3.38 (0.32)	1.36 (0.50)	0.10 (0.05)	
	Wyo. Crude	Sur. - 2 cm	268 (18)	1.53 (0.92)	1.70 (0.34)	0.21 (0.08)	1.03 (0.02)
		2 cm - 4 cm	251 (61)	2.54 (1.42)	1.54 (0.38)	0.18 (0.08)	1.09 (0.04)
		4 cm - 6 cm	270 (14)	2.89 (0.45)	1.84 (0.38)	0.17 (0.06)	
		> 6 cm	245 (18)	3.12 (0.74)	1.34 (0.08)	0.16 (0.02)	
Dark[b]	Control	Sur. - 2 cm	212	1.39	0.82	0.04	1.15
		2 cm - 4 cm	248	2.04	0.54	0.06	1.15
		4 cm - 6 cm	321	1.88	0.45	0.05	
		> 6 cm	383	4.54	0.33	0.14	
	S. La. Crude	Sur. - 2 cm	409	1.44	2.36	0.26	1.17
		2 cm - 4 cm	199	2.18	1.45	0.21	1.12
		4 cm - 6 cm	225	3.28	1.84	0.26	
		> 6 cm	291	2.56	1.25	0.42	
	Wyo. Crude	Sur. - 2 cm	382	2.16	1.56	0.17	1.06
		2 cm - 4 cm	230	2.55	0.38	0.16	1.15
		4 cm - 6 cm	226	2.10	0.52	0.13	
		> 6 cm	283	3.22	0.35	0.15	

[a]All reported measurements for diurnal microcosms were mean values from three replicate microcosms.

[b]All reported measurements for dark microcosms were results from a single microcosm.

Table 13. Values at four depths of sediment parameters on the final day of the New Fork Lake microcosm experiment. Values in parentheses are standard deviations.

Condition	Treatment	Depth	Total Phos (µg/g Dry Wt.)	NH_3-N (µg/g Wet Wt.)	NO_3-N (µg/g Wet Wt.)	NO_2-N (µg/g Wet Wt.)	Percent Organic Matter
Diurnal[a]	Control	Sur. - 2 cm	279 (38)	1.63 (--)	0.75 (0.44)	0.02 (0.004)	1.38 (0.18)
		2 cm - 4 cm	309 (125)	2.54 (0.98)	0.70 (0.17)	0.02 (0.001)	1.41 (0.01)
		4 cm - 6 cm	342 (71)	4.15 (3.14)	0.69 (0.44)	0.03 (0.02)	1.19 (0)
		> 6 cm	309 (49)	6.32 (2.18)	0.80 (0.11)	0.03 (0.01)	1.31 (0.27)
	S. La. Crude	Sur. - 2 cm	346 (121)	8.54 (3.37)	1.22 (0.58)	0.05 (0.01)	1.31 (0.30)
		2 cm - 4 cm	306 (58)	9.04 (0.15)	1.00 (0.50)	0.05 (0.02)	1.27 (0.04)
		4 cm - 6 cm	344 (154)	6.73 (1.97)	0.76 (0.30)	0.04 (0.001)	1.18 (0.08)
		> 6 cm	299 (39)	10.20 (1.49)	0.93 (0.22)	0.04 (0.002)	1.36 (0.11)
	Wyo. Crude	Sur. - 2 cm	379 (38)	4.90 (0.28)	0.58 (0.26)	0.02 (0.001)	1.46 (0.10)
		2 cm - 4 cm	523 (148)	7.20 (0.91)	0.65 (0.36)	0.04 (0.03)	1.28 (0.05)
		4 cm - 6 cm	469 (112)	8.31 (1.73)	0.55 (0.20)	0.04 (0.02)	1.29 (0.04)
		> 6 cm	364 (38)	9.59 (2.14)	0.63 (0.10)	0.04 (0.03)	1.22 (0.06)
Dark[b]	Control	Sur. - 2 cm	427	7.74	0.57	0.02	1.42
		2 cm - 4 cm	518	4.85	0.72	0.02	1.35
		4 cm - 6 cm	362	9.05	0.82	0.04	--
		> 6 cm	352	7.55	0.67	0.05	1.31
	S. La. Crude	Sur. - 2 cm	365	7.07	0.37	0.02	1.87
		2 cm - 4 cm	416	8.93	1.42	0.02	1.37
		4 cm - 6 cm	368	9.29	0.38	0.02	1.31
		> 6 cm	304	11.48	0.37	0.02	--
	Wyo. Crude	Sur. - 2 cm	320	5.47	0.93	0.02	1.48
		2 cm - 4 cm	433	7.89	0.75	0.02	1.32
		4 cm - 6 cm	375	8.52	0.33	0.02	1.34
		> 6 cm	418	10.08	0.39	0.02	1.65

[a]All reported measurements for diurnal microcosms were mean values from three replicate microcosms.

[b]All reported measurements for dark microcosms were results from a single microcosm.

Table 14. Values at four depths of sediment parameters 20 days after oil was added to New Fork Lake microcosms.

Condition	Treatment	Depth	Total Phos (µg/g Dry Wt.)	NH_3-N (µg/g Wet Wt.)	NO_3-N (µg/g Wet Wt.)	NO_2-N (µg/g Wet Wt.)
Light	Control	Sur. - 2 cm	350	9.64	0.44	0.02
		2 cm - 4 cm		15.3	0.69	0.02
		4 cm - 6 cm		16.8	0.74	0.02
		> 6 cm	317	18.0	0.76	0.02
	S. La. Crude	Sur. - 2 cm	310	11.7	1.24	0.02
		2 cm - 4 cm		13.1	1.40	0.02
		4 cm - 6 cm		13.3	1.15	0.02
		> 6 cm	320	14.9	1.88	0.02
	Wyo. Crude	Sur. - 2 cm	367	11.6	1.27	0.02
		2 cm - 4 cm		13.2	2.56	0.02
		4 cm - 6 cm		14.8	1.55	0.02
		> 6 cm	323	15.6	3.33	0.03

single microcosm. Thus, differences cited for dark microcosm treatments are not based on statistical analyses. Treatment initiation occurred on day 42 of the experiment (marked on Figures 6-32) even though data are presented from day zero.

Alkalinity values for BL control microcosms and the two oiled treatments throughout time are presented in Figure 7. Alkalinity values in diurnal microcosms did not vary greatly throughout time. However, mean values for oiled treatments were greater than for the unoiled control on the final three measurement dates. No difference existed between the two oiled treatments on any date. A similar pattern existed for dark BL microcosms although the difference was not as great. Figure 8 presents NFL microcosm alkalinity results. Differences between diurnal oiled microcosms and controls after the addition of oil (day 42) were not statistically significant. The dark control NFL microcosm had lower alkalinity values than either treatment on all dates except day 80 after treatment initiation.

Values for pH in BL diurnal microcosms were reduced by treatment (Figure 9). An identical pattern existed in BL dark microcosms. No differences were observed among oiled treatments for diurnal microcosms and only slight differences occurred among dark microcosms. As in BL microcosms, pH values were higher for dirunal control NFL microcosms than for oiled treatments (Figure 10). Additionally, South Louisiana Crude (SLC) treated microcosms had a higher pH on day 90 than did Wyoming Crude (WC) treated microcosms. The pH of dark NFL microcosms was not changed by oil addition.

Orthophosphate concentrations appear to be quite variable throughout the study in BL diurnal microcosms; probably because the concentrations were at the lower detection limit of the chemical analyses. No significant difference between controls and treatments was detected for diurnal microcosms (Figure 11). Although dark microcosm orthophosphate concentrations were also variable, consistent differences appear between the control and treatments. Control concentrations varied around 8 µg/l (the concentration of orthophosphate in fresh BL medium). In contrast, oil treated microcosm orthophosphate concentrations decreased to between zero to 3 µg/l and remained there.

The pattern of orthophosphate concentration in the NFL experiment was quite different from that in the BL experiment (Figure 12). Oil-treated diurnal microcosms had higher orthophosphate concentrations than the control microcosms past day 60 (WC) and 70 (SLC). There were no significant concentration differences between the two oil types. Dark microcosms also displayed marked differences between treatments and the control. Whereas the control microcosm orthophosphate concentration remained below 10 µg/l after treatment initiation, oil-treated microcosms dramatically increased in concentration (up to 200 µg/l) after being impacted by oil. SLC treated microcosms appeared to reach higher orthophosphate concentrations than WC treated systems on days 80 and 90.

Nitrate concentrations were apparently not affected by oil treatments in diurnal BL microcosms (Figure 13). However, treated dark BL microcosms consistently had lower nitrate concentrations beginning immediately after treatment initiation (day 42). Nitrate levels for diurnal NFL microcosms were also unaffected by either oil type (Figure 14). The extremely high concentration reported on day 90 for WC microcosms almost certainly resulted from technician error. Dark NFL microcosms exhibited the same pattern for nitrate as in BL; that is, higher values for the control microcosm than oiled treatments following treatment initiation (with the exception of SLC on day 70).

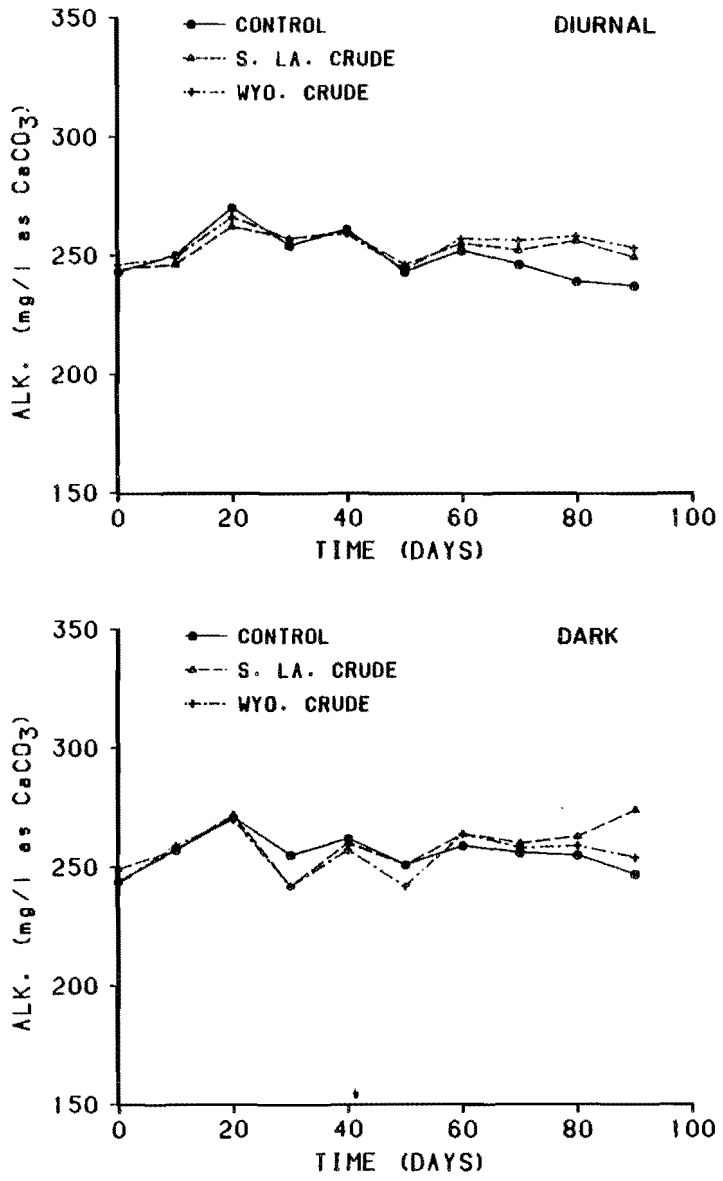


Figure 7. Alkalinity in Bear Lake microcosms.

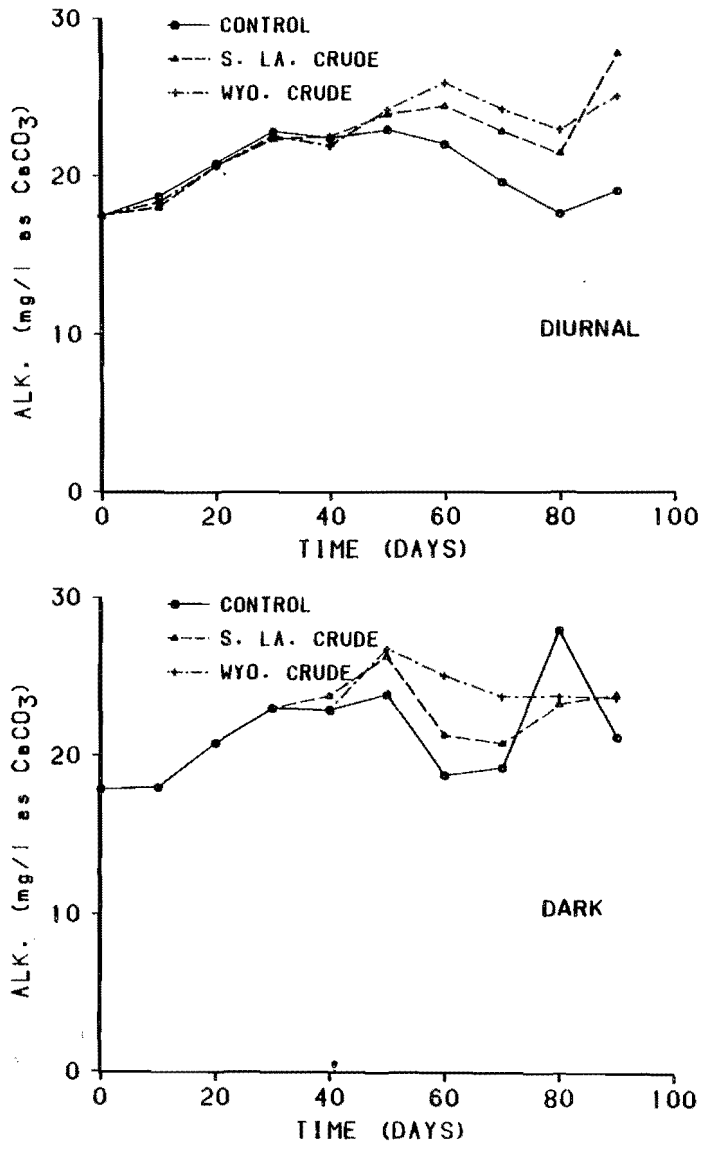


Figure 8. Alkalinity in New Fork Lake microcosms.

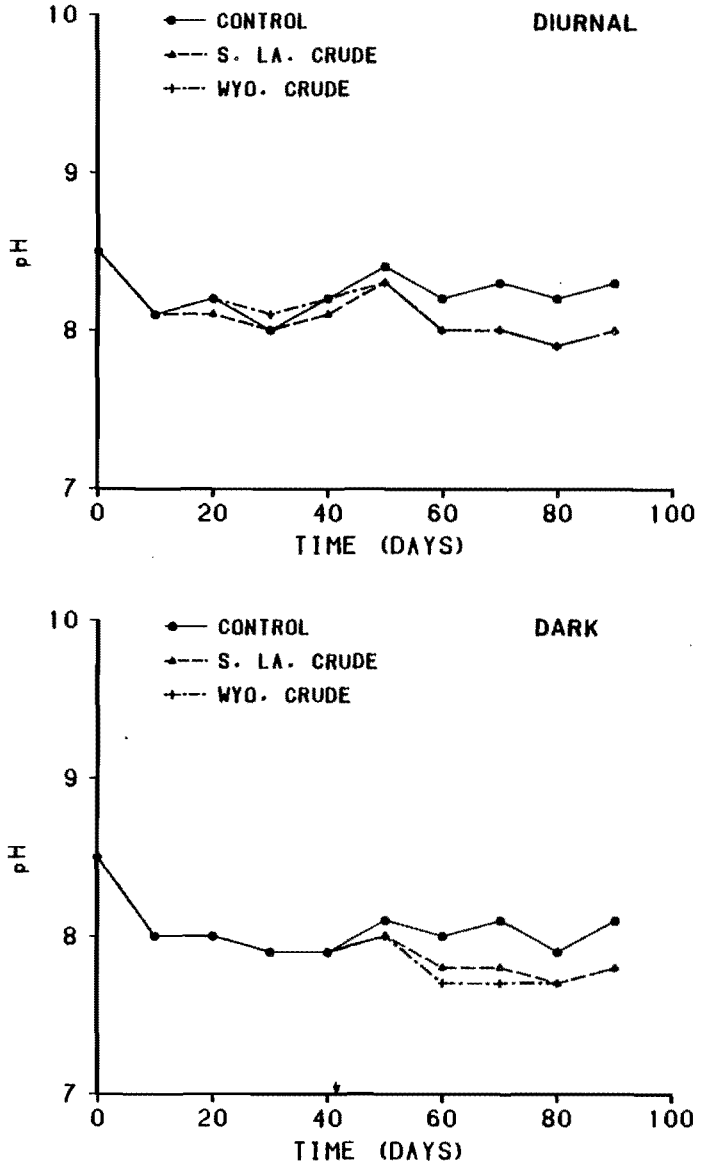


Figure 9. pH in Bear Lake microcosms.

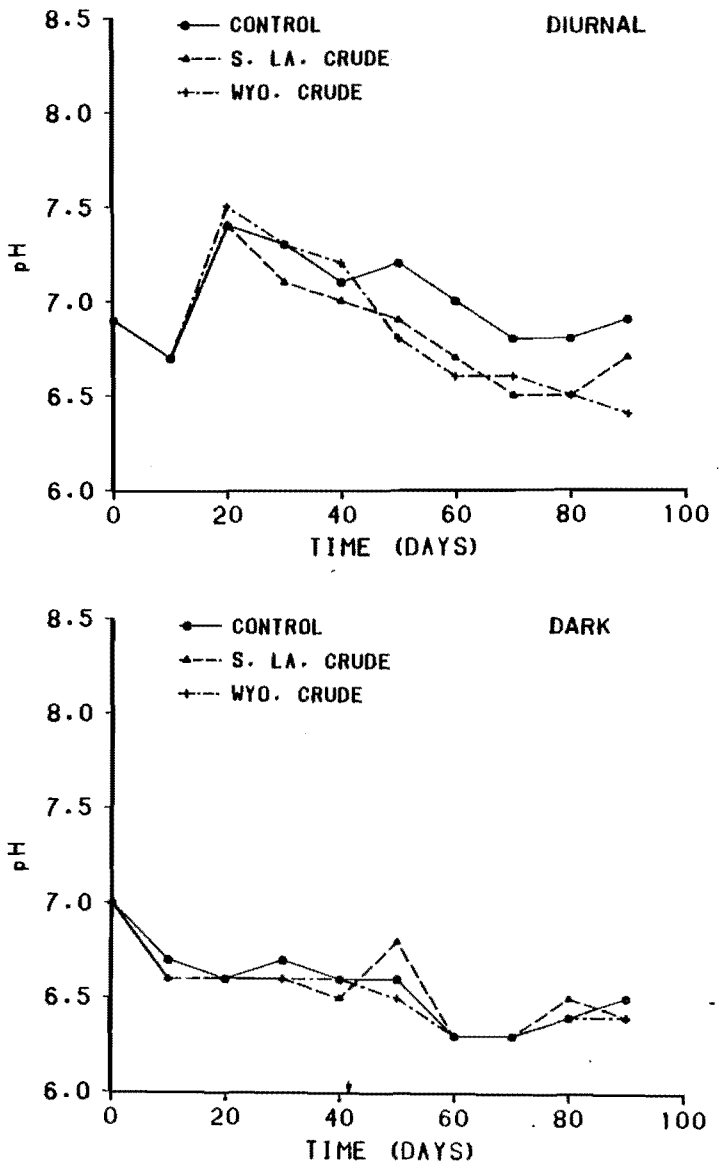


Figure 10. pH in New Fork Lake microcosms.

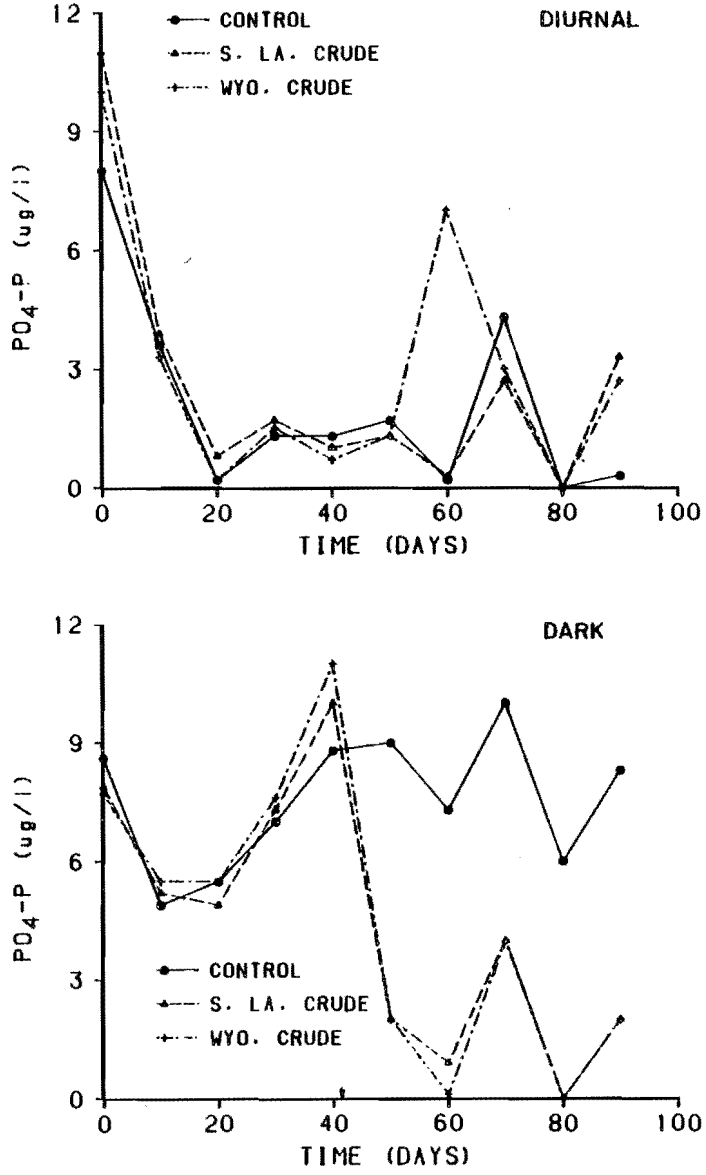


Figure 11. Orthophosphate in Bear Lake microcosms.

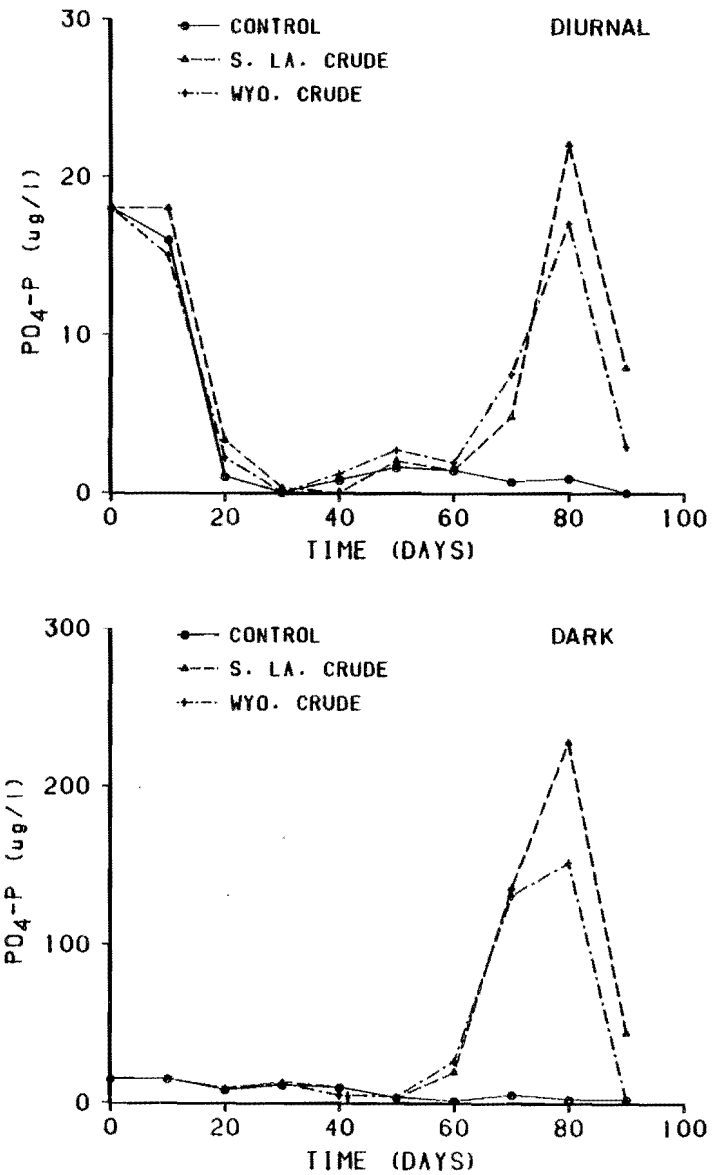


Figure 12. Orthophosphate in New Fork Lake microcosms.

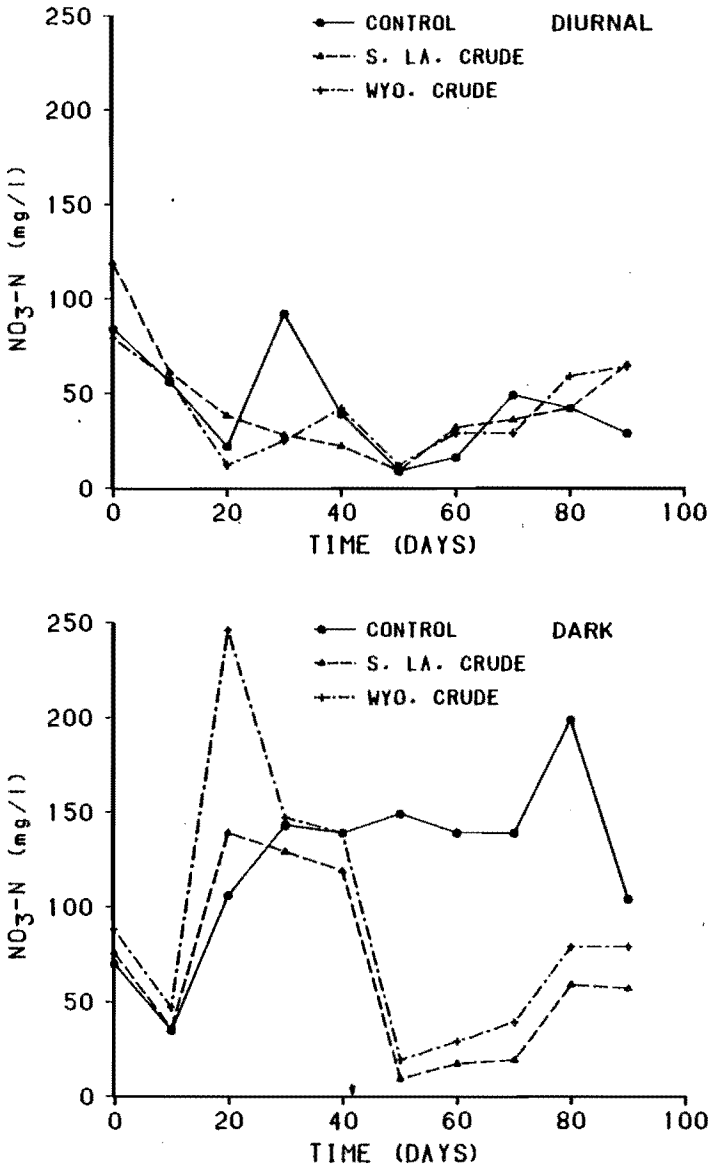
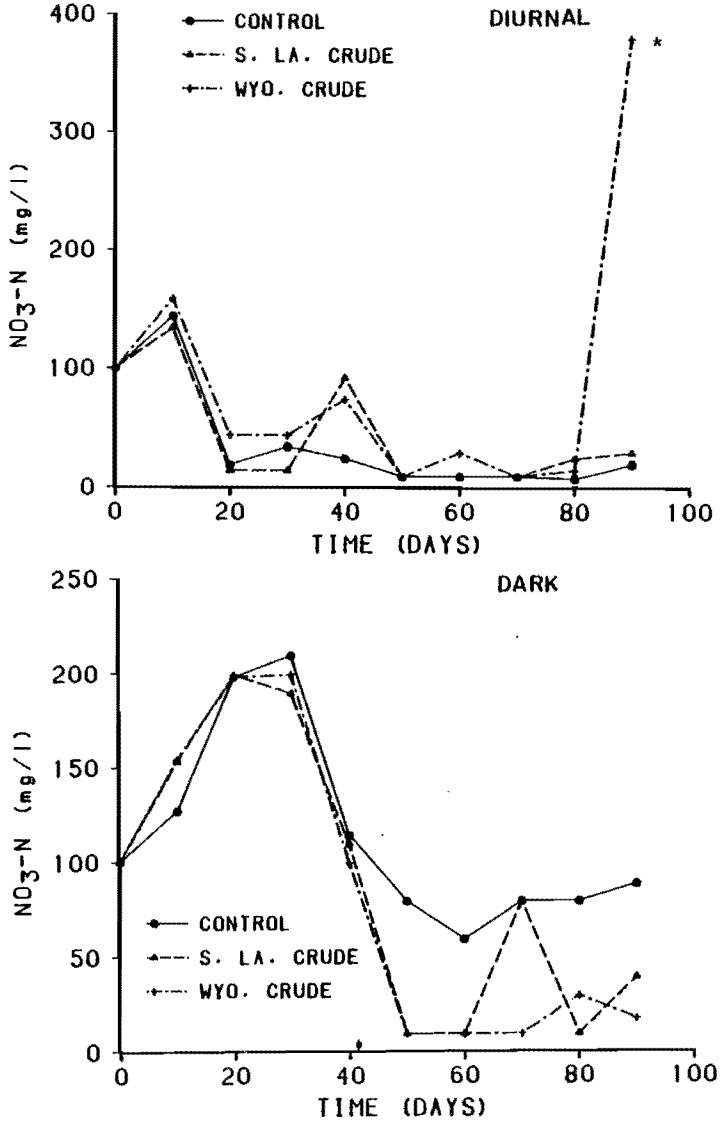


Figure 13. Nitrate in Bear Lake microcosms.



*This high concentration would appear to be due to contamination or technician error.

Figure 14. Nitrate in New Fork Lake microcosms.

Dissolved oxygen concentrations for both light conditions in both lakes declined markedly after treatment (Figures 15 and 16). Also, WC diurnal microcosms were lower in dissolved oxygen than corresponding SLC diurnal microcosms by day 90 in both lake studies.

Total organic carbon (TOC) concentrations were greater for BL diurnal microcosms treated with WC than controls after day 60; SLC treatments had greater concentration than controls after day 70 (Figure 17). BL dark microcosms treated with oil also had higher TOC values following treatment initiation. TOC values in NFL diurnal treatments were also higher than controls after day 50 (Figure 18).

Gaseous phase composition

The mole fraction of oxygen gas in the gaseous phase of the microcosms is presented for the various treatments in Figures 19 and 20 for BL and NFL, respectively. As with dissolved oxygen in the aqueous phase, there is a striking reduction in both lake experiments following oil addition (day 42) under both diurnal and dark conditions. The difference between controls and both treatments was statistically significant after day 50 in BL and day 40 in NFL. Additionally, the mole fraction of oxygen was greater in the SLC diurnal systems than the WC systems on day 90 in BL and days 70 and 80 in NFL. The major difference between lake experiments regarding this parameter is that the dark control in NFL reached lower oxygen values than the dark control in BL.

Figures 21 and 22 display the mole fractions of carbon dioxide in the microcosms' gaseous phase for BL and NFL experiments, respectively. In both cases, the fractions dropped dramatically (except for NFL dark microcosms). Significant differences between controls and treatments occur on every date for diurnal microcosms following oil addition. WC diurnal system had significantly higher carbon dioxide levels than SLC microcosms on day 90 in BL and days 50, 60, and 70 in NFL experiments.

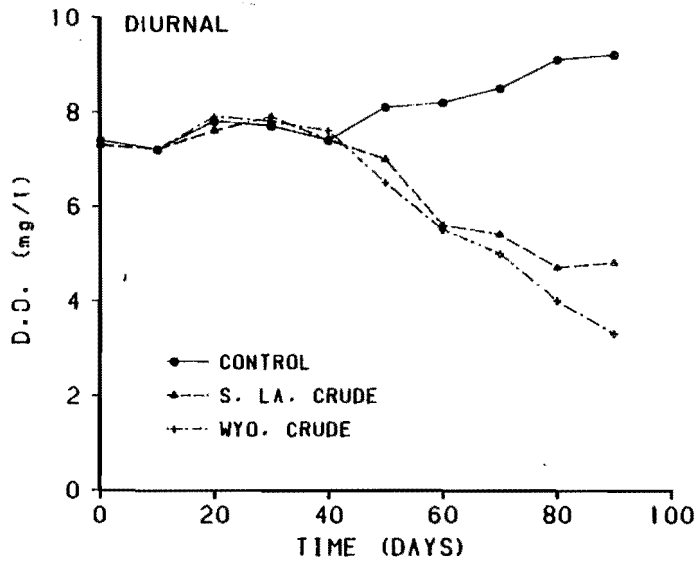
The mole fractions of nitrogen gas in the microcosms were also higher in diurnal treatments than controls (significant after day 62 in BL and 50 in NFL) (Figures 23 and 24). Nitrogen was generally higher in WC diurnal systems than in SLC diurnal systems. BL dark microcosms followed the same pattern throughout time as did the diurnal systems. However, NFL dark microcosms did not demonstrate consistent inter-treatment differences.

Methane was never detected in BL microcosms but, with the exception of the dark control, it was produced and detected in NFL systems (Figure 25). Significant differences between control and treatments did not exist.

Accumulations of other constitutents

Accumulations of various other constituents were determined throughout the microcosm experiments. Mass balance calculations were corrected for the amount of the constituent added to the microcosm in fresh medium or removed during the medium exchange procedure on a daily basis. Thus, the values presented for constituent accumulation reflect only changes that occurred within the microcosms. Mechanisms leading to such changes include nutrient release from the sediment and oxygen consumption by decomposers. Positive values indicate the given constituent was accumulating in the microcosm whereas negative values mean the constituent was being immobilized or otherwise altered.

Nutrients. The accumulations of nitrate and phosphate for dark microcosms are shown in Figures 26 and 27 for BL and NFL, respectively. Nitrate and phosphate are the only nutrients for which this analysis is presented because the critical nutrients (N) and (P) were



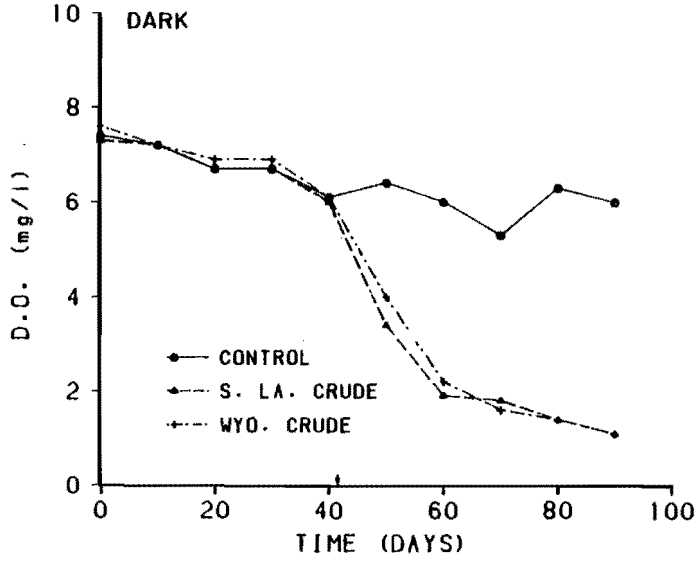
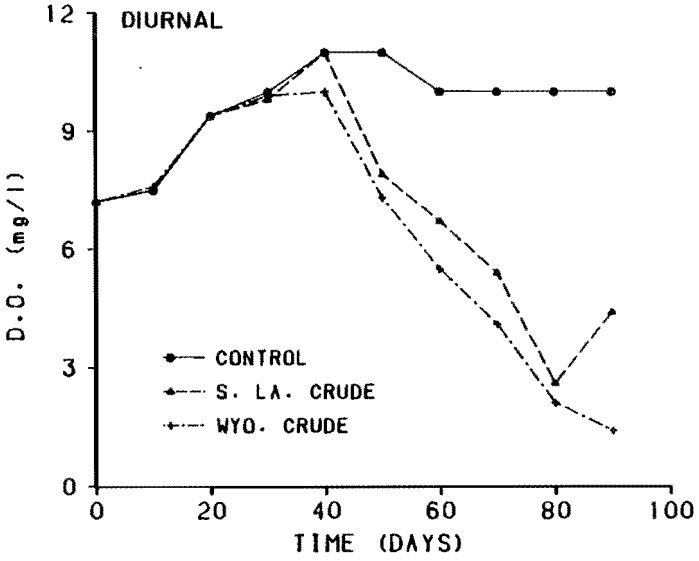


Figure 15. Dissolved oxygen in Bear Lake microcosms.



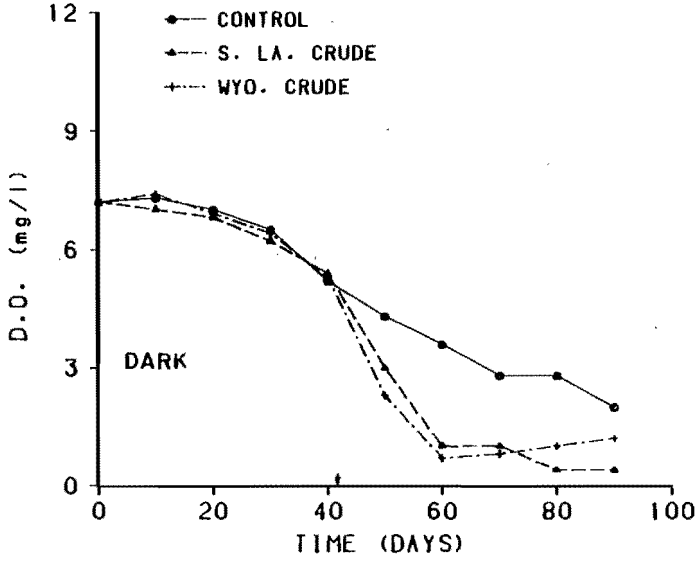


Figure 16. Dissolved oxygen in New Fork Lake microcosms.

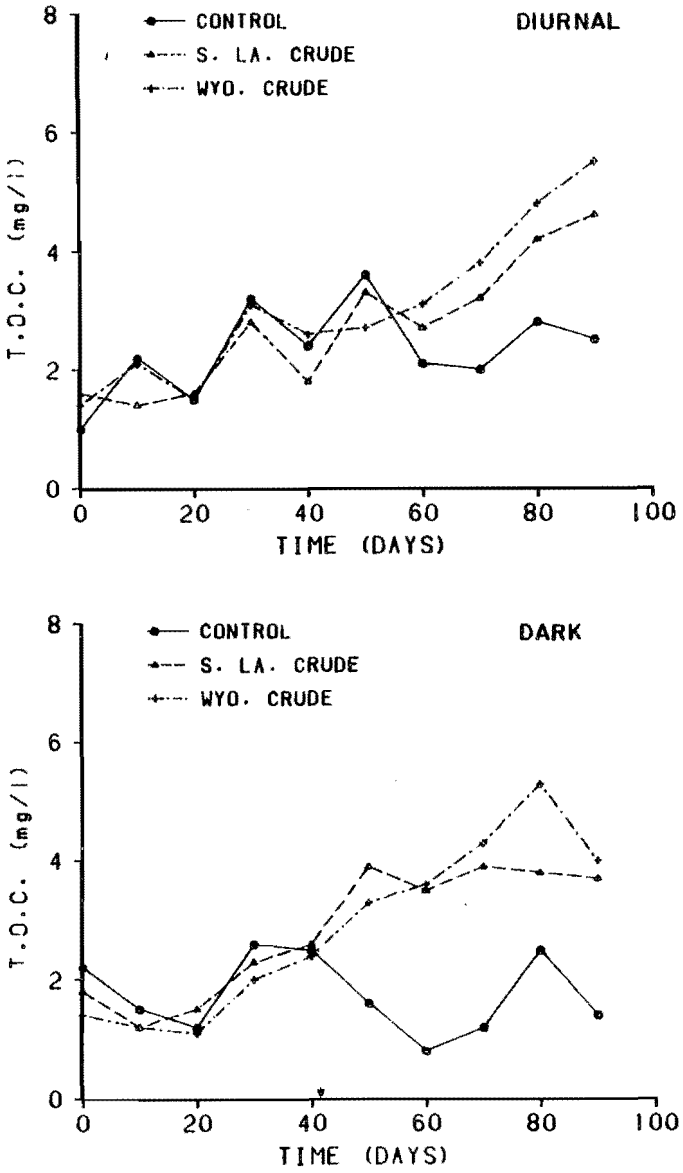


Figure 17. Total organic carbon in Bear Lake microcosms.

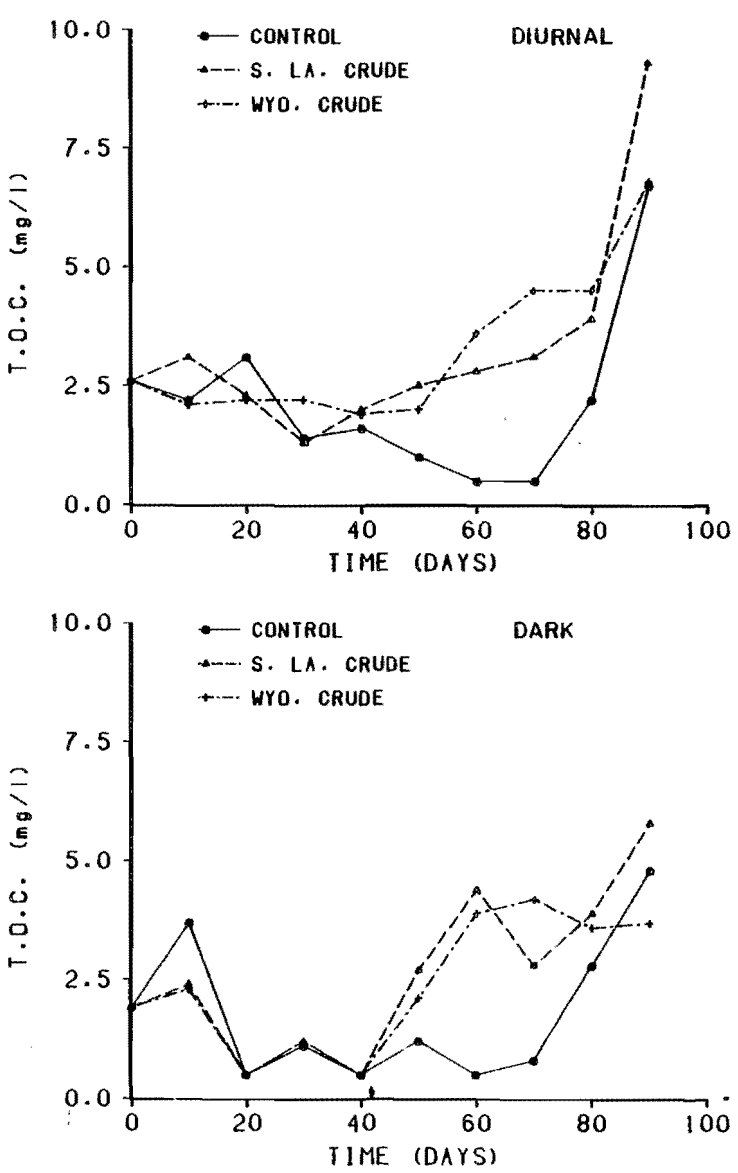


Figure 18. Total organic carbon in New Fork Lake microcosms.

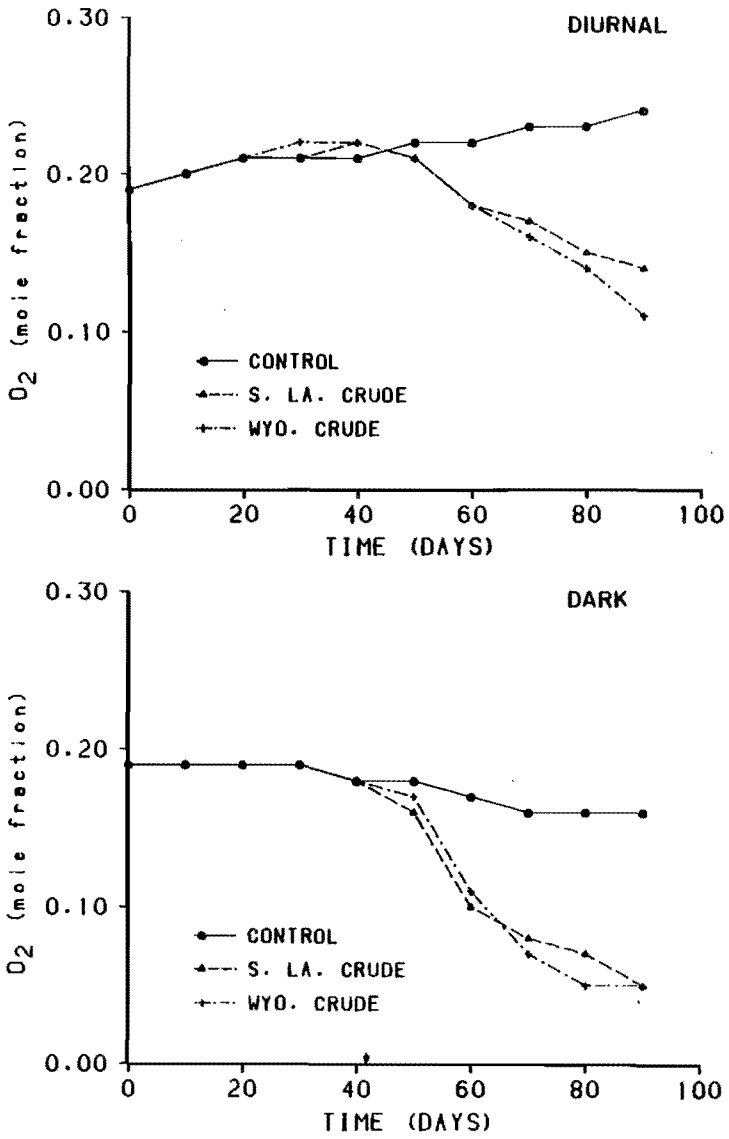


Figure 19. Oxygen in the gaseous phase of Bear Lake microcosms.

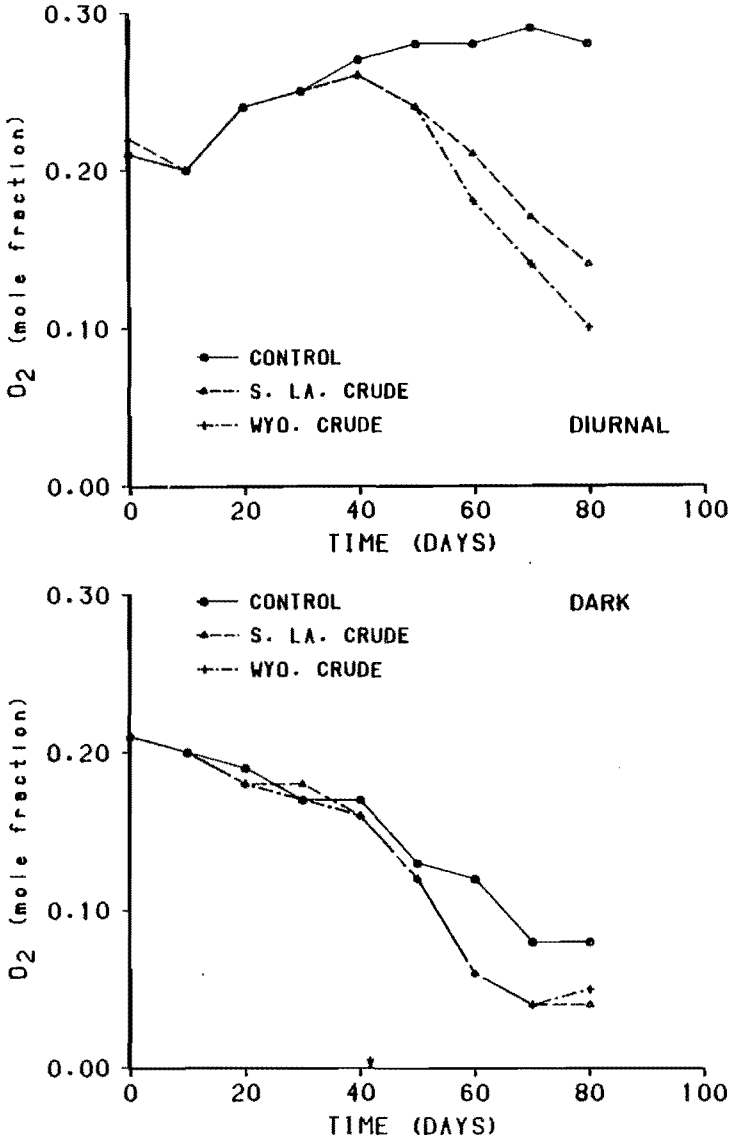


Figure 20. Oxygen in the gaseous phase of New Fork Lake microcosms.

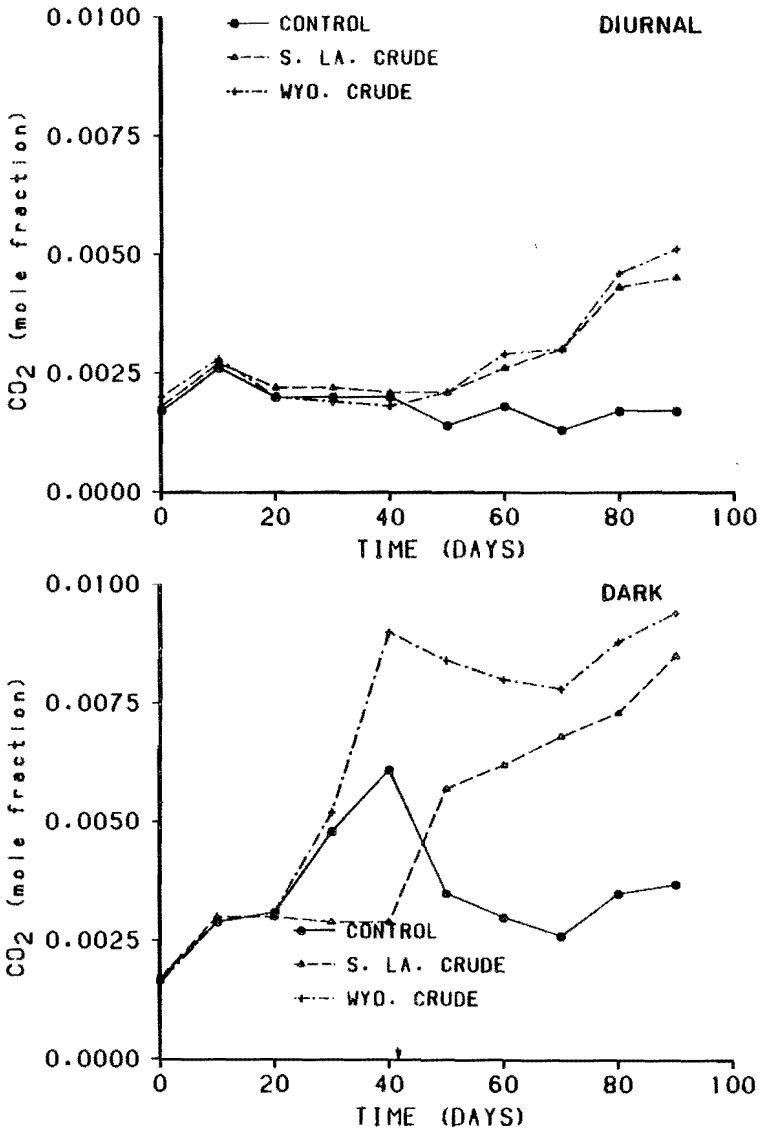


Figure 21. Carbon dioxide in the gaseous phase of Bear Lake microcosms.

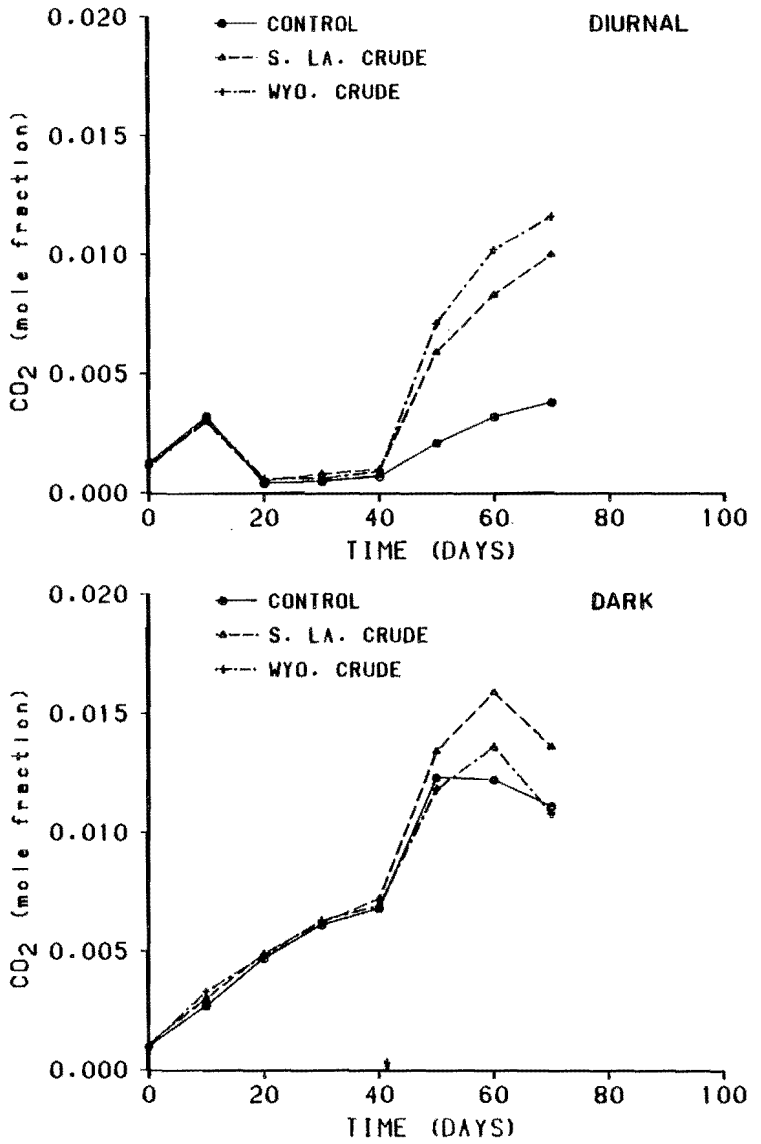


Figure 22. Carbon dioxide in the gaseous phase of New Fork Lake microcosms.

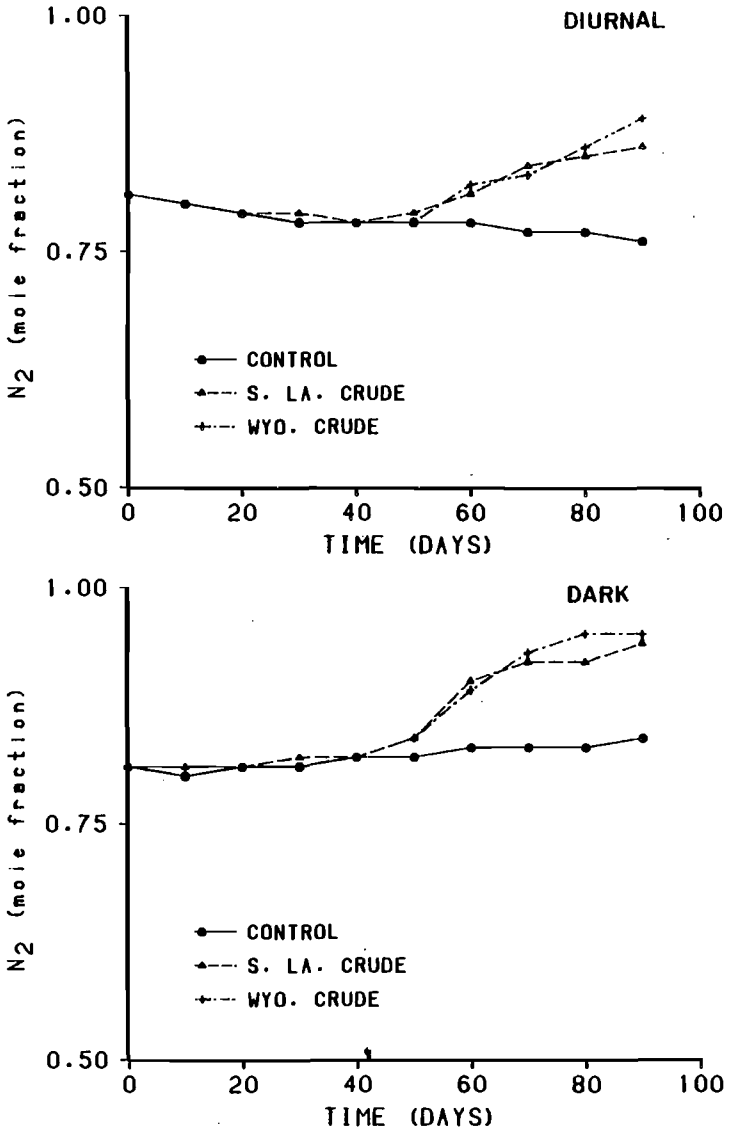


Figure 23. Nitrogen gas in the gaseous phase of Bear Lake microcosms.

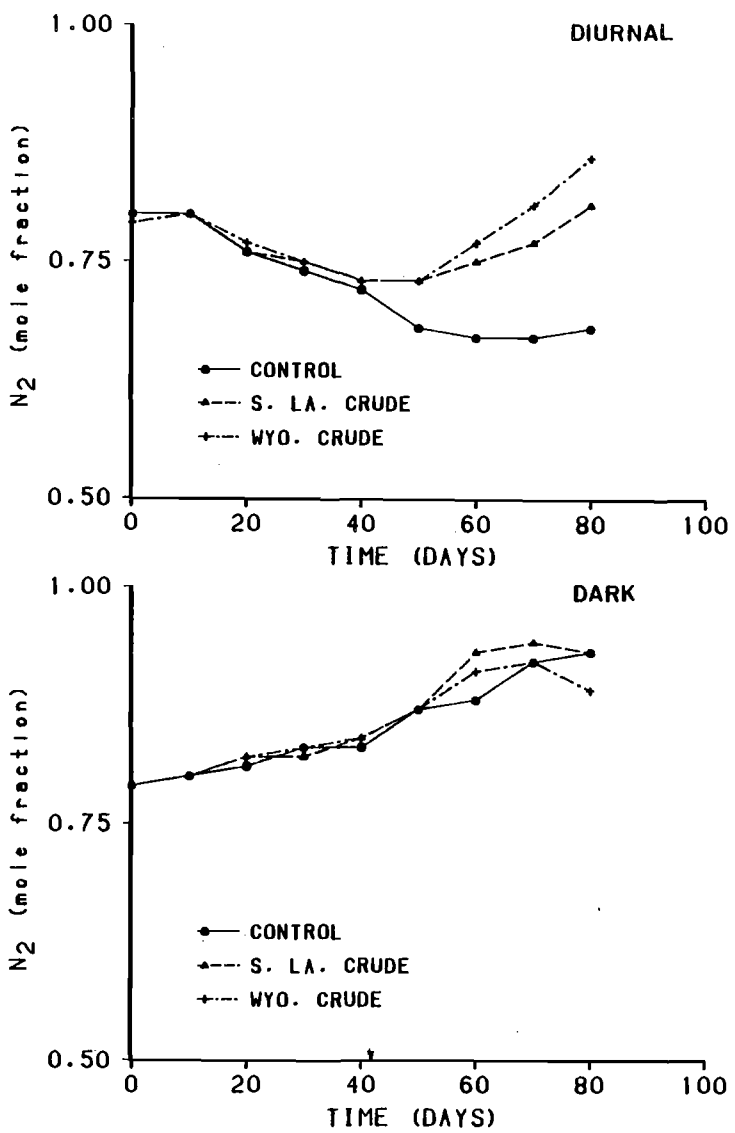


Figure 24. Nitrogen gas in the gaseous phase of New Fork Lake microcosms.

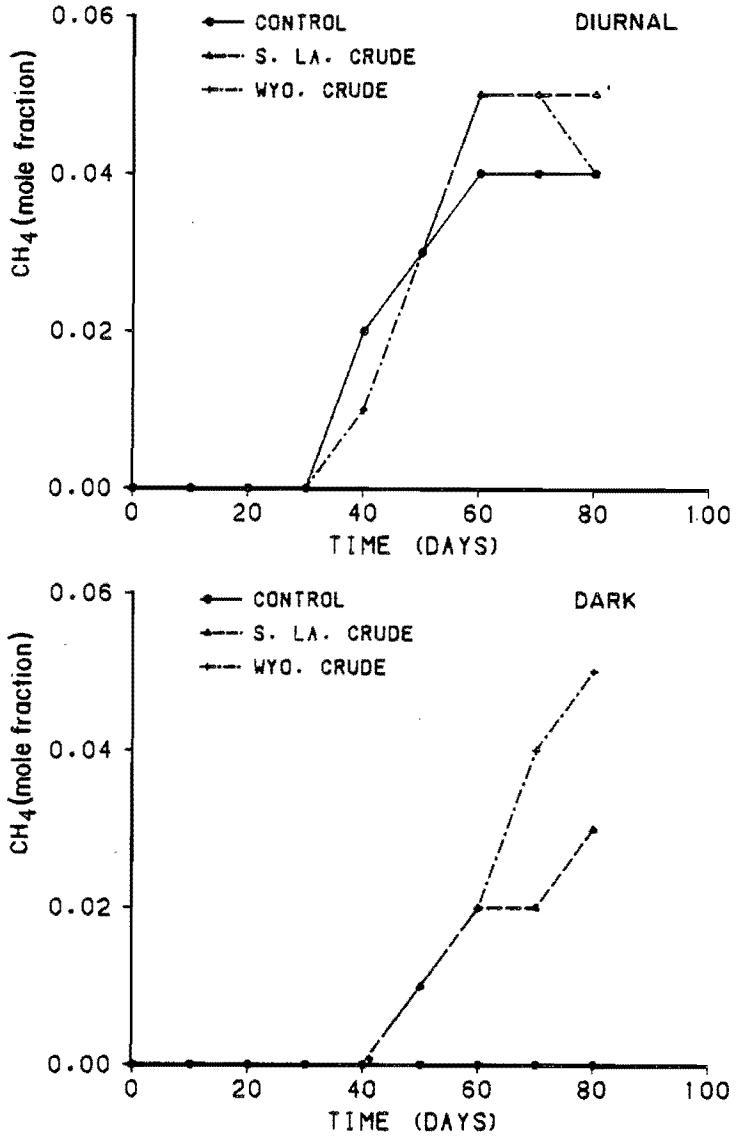


Figure 25. Methane in the gaseous phase of New Fork Lake microcosms.

added to the microcosms in this form. Results of the diurnal microcosms are not presented because nutrient dynamics in those systems were results of both photosynthesis and respiration, so clear conclusions cannot be drawn (only respiration occurred in the dark systems).

Nitrate accumulated in all dark BL microcosms before treatment initiation; thus nitrate was being released to the aqueous phase from the sediments. After treatments were established, the control system continued to accumulate nitrate but oil treatments immediately began to immobilize the nutrient.

Phosphate was immobilized in all BL microcosms during the first 20 days (Figure 26). Afterward, phosphate levels in the control microcosms remained fairly constant, thus phosphate neither accumulated nor was it immobilized. In contrast, phosphate was immobilized by the oil treatments.

Nitrate accumulated in the aqueous phase of all NFL microcosms through day 30. Following this initial phase,

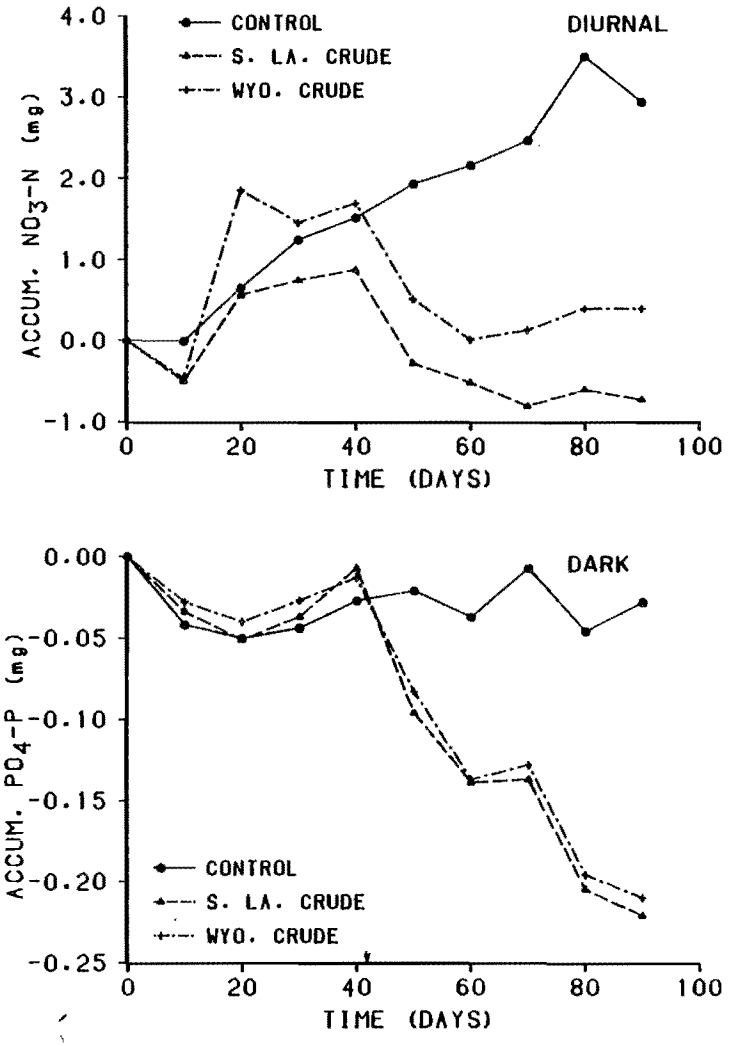


Figure 26. Nitrate (upper graph) and phosphate (lower graph) accumulation in the aqueous phase of Bear Lake dark microcosms.

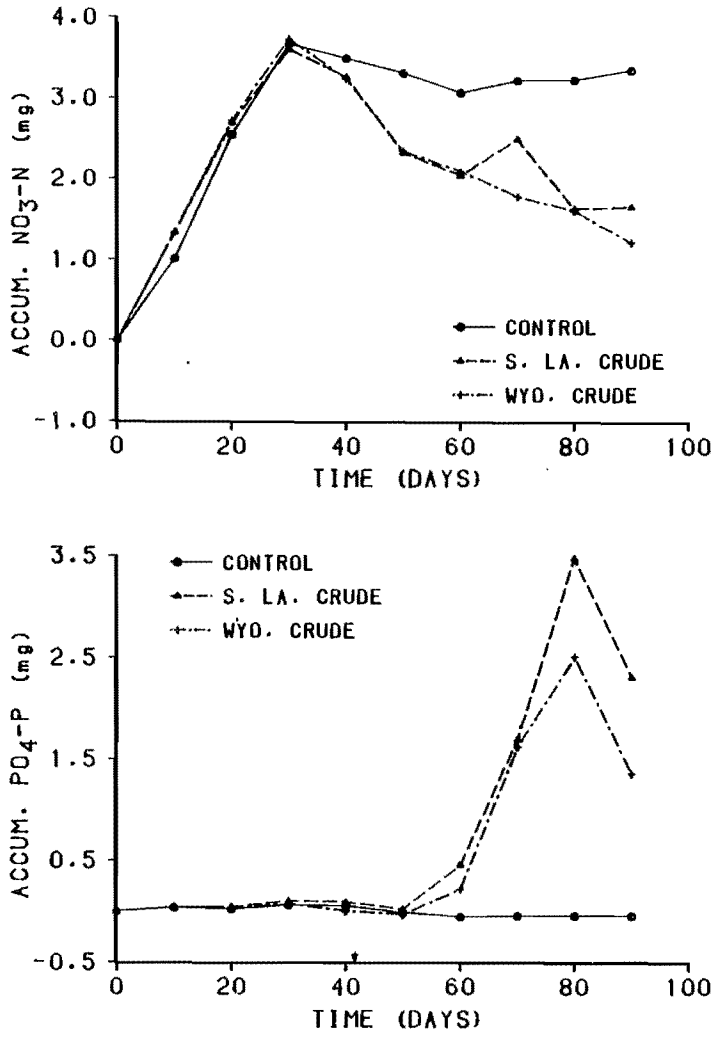


Figure 27. Nitrate (upper graph) and phosphate (lower graph) accumulation in the aqueous phase of New Fork Lake dark microcosms.

nitrate was neither accumulated nor immobilized in the control, but a net immobilization occurred in the oil-treated microcosms.

Phosphate dynamics in dark NFL microcosms were very different than in the dark BL microcosms. There was no net accumulation (or immobilization) of phosphate in the control microcosm during the entire experiment nor in treated microcosms during the first 50 days. However, after day 50, a dramatic rate of phosphate accumulation occurred in oil-treated microcosms. Some of this accumulated phosphate was lost from the aqueous phase between days 80 and 90.

Gases. Total gas accumulation after day 10 was continuous and positive for BL diurnal control microcosms (Figure 28). Prior to treatment initiation the same was true for treatments, however, the trend reversed after treatment. The control BL dark microcosm consumed gas throughout the experiment, but at a lower rate than did the oiled systems.

NF diurnal control and treatment microcosms followed similar patterns of net gas accumulation (or consumption) (Figure 29). Initial accumulations were followed by net consumption in all microcosms. WC microcosms consumed gas to a significantly greater extent than either control or SLC systems. All dark NFL microcosms had a net consumption of gas during the experiment. The control microcosm consumed more gas then either treatment.

Oxygen slowly accumulated in BL diurnal control microcosms but was rapidly consumed in both treatments after oil addition (Figure 30). Oxygen consumption for the dark counterparts was slow in the control throughout the experiment but rapid for treatments after oil addition.

Oxygen dynamics for NFL systems had the same data trends as for BL (Figure 31), but the magnitude of oxygen accumulation in diurnal control was greater, and a higher rate of oxygen consumption in the dark control occurred during the NFL experiment.

Carbon dioxide accumulated in the gaseous phase of all microcosms throughout the experiments (Figures 32 and 33). The rate of accumulation was greater for treatments than controls in both experiments under both light conditions.

Biological analyses

Terminal plant biomass. Results of biomass analyses performed at the end of microcosm experiments are presented in Tables 15 and 16 for BL and NFL studies, respectively. Biomass measurements included both green plant and microbial communities; no attempt was made to separate the biomass by function groups. Biomass measurements were performed at three sites within the microcosms; the water column, the microcosm sides, and the sediment surface. Variability of the results lessen the ability to detect statistically significant differences, especially in the NFL experiment with only two replicates per treatment. However, there were clear patterns within these data for both microcosm experiments.

Biomass in the water column was greater for oil treated than for control microcosms under both light conditions in both lakes. However, statistically significant differences existed only for the control-SLC comparison in NFL.

A clear pattern did not exist for biomass differences between controls and oil treatments on the microcosm sides. The only significant difference was in the BL comparison between SLC and WC treatments.

Sediment surface biomass was greater in control microcosms than either oiled treatments in both experiments. Mean differences were from 1.4 to 5 times greater for controls than

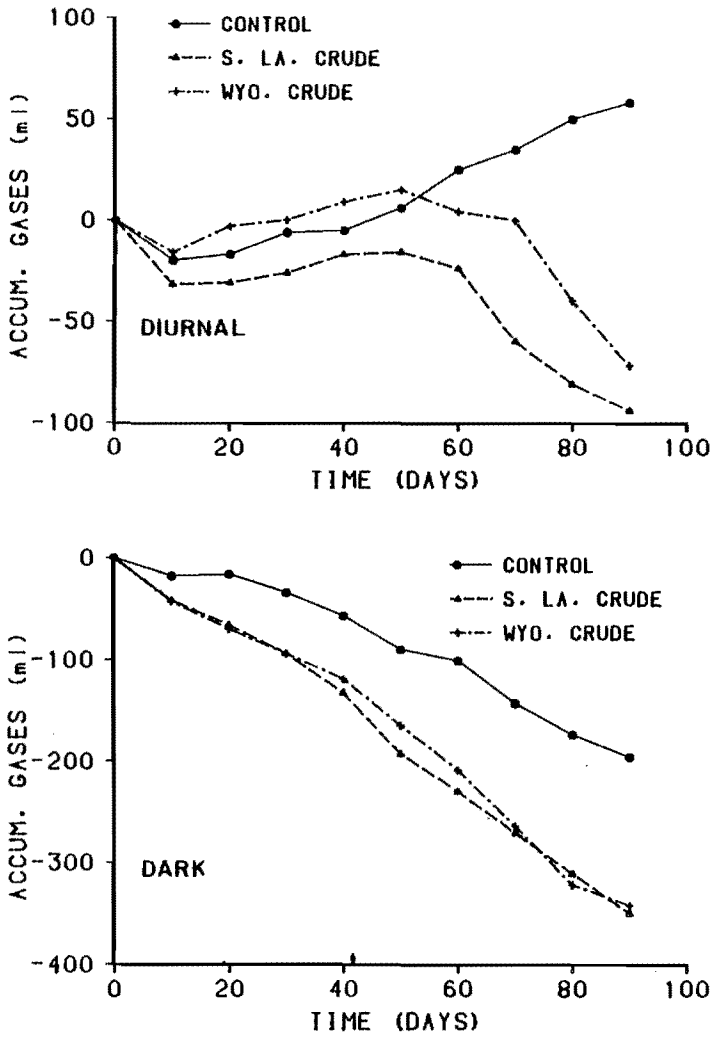


Figure 28. Total gas accumulation in Bear Lake microcosms.

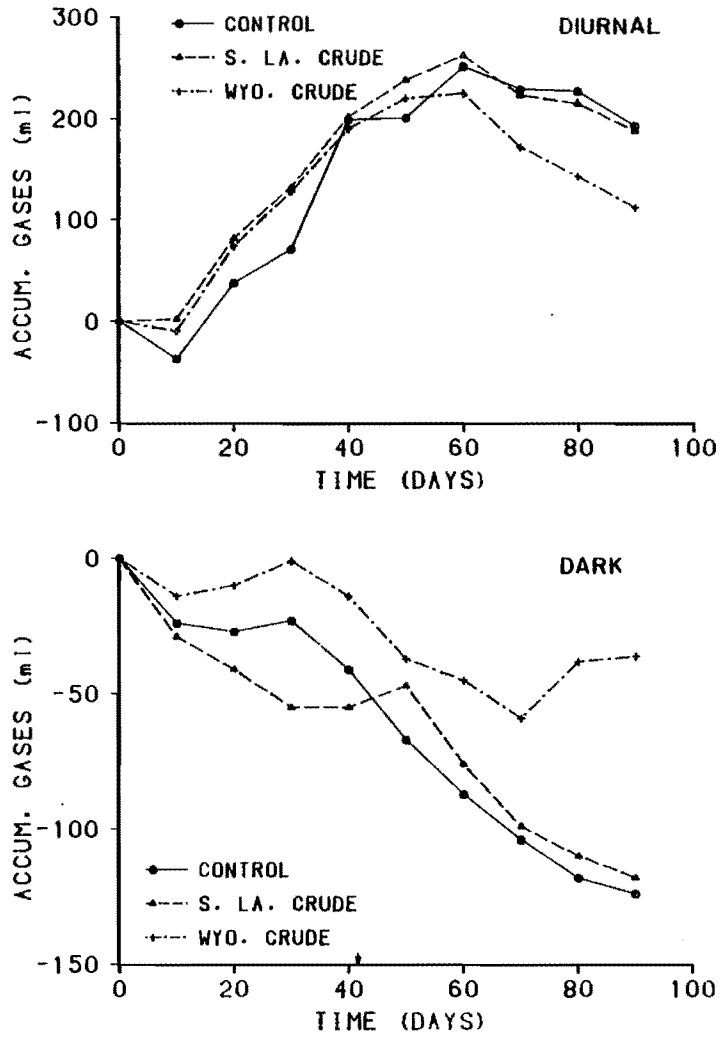
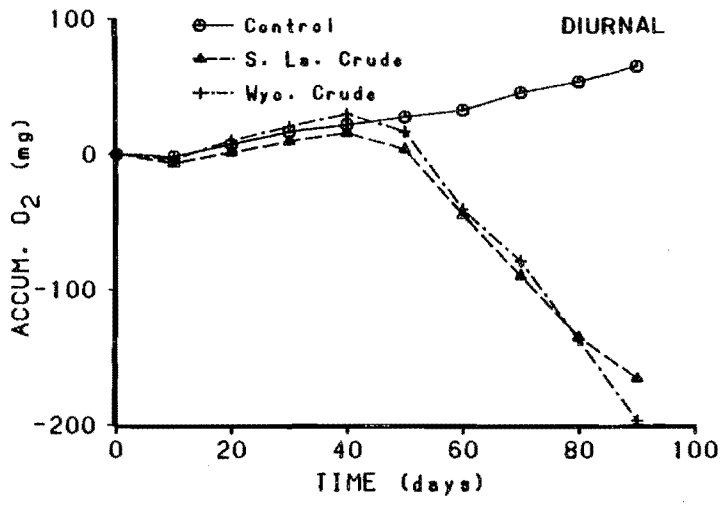


Figure 29. Total gas accumulation in New Fork Lake microcosms.



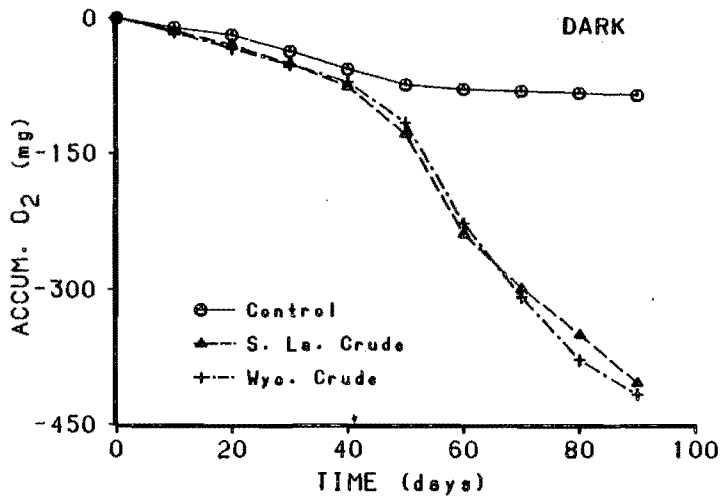
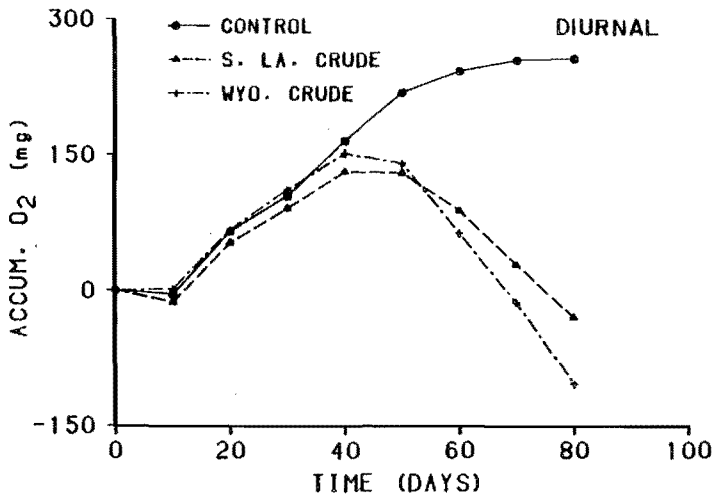


Figure 30. Oxygen accumulation in the gaseous phase of Bear Lake microcosms.



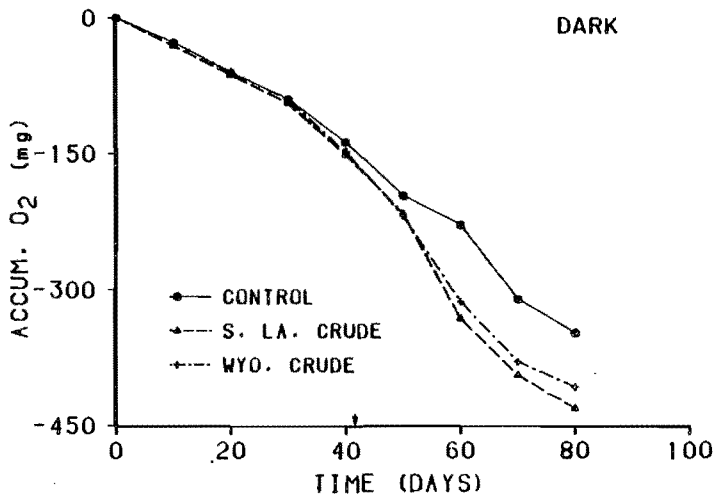
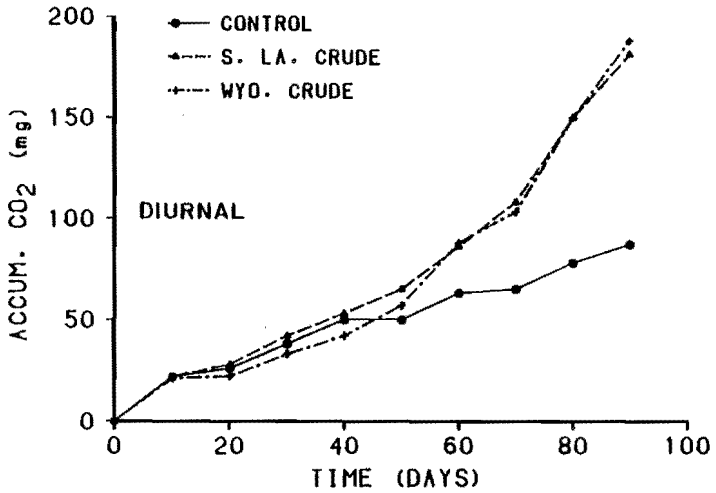


Figure 31. Oxygen accumulation in the gaseous phase of New Fork Lake microcosms.



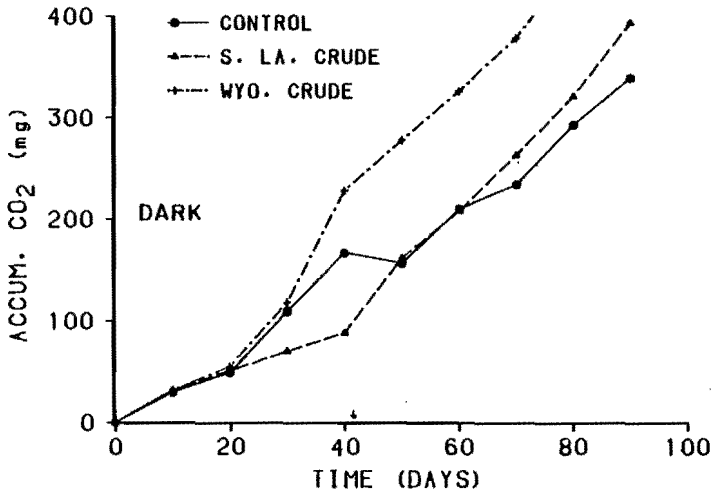
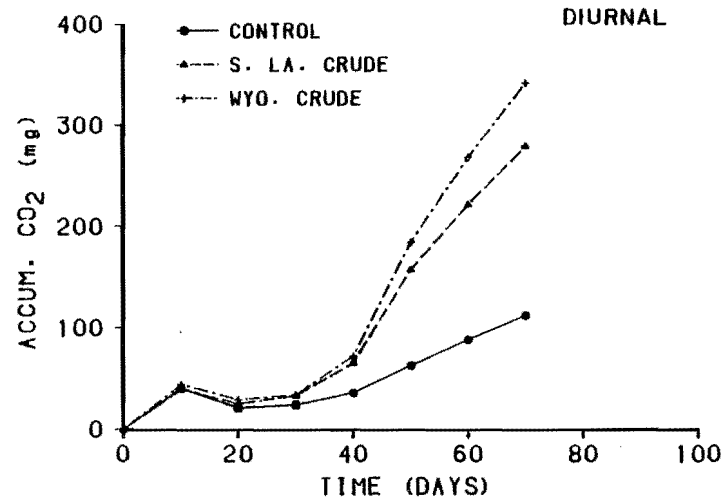


Figure 32. Carbon dioxide accumulation in Bear Lake microcosms.



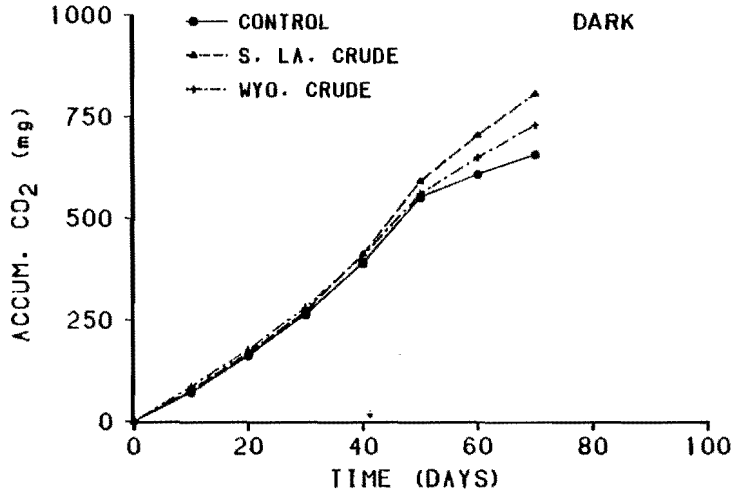


Figure 33. Carbon dioxide accumulation in New Fork Lake experiment.

Table 15. Biomass analyses and test results for statistically significant differences for the Bear Lake microcosms.

Condition	Treatment	Water Column (mg AFDW*)	Microcosm Sides (mg AFDW)	Sediment Surface (mg AFDW)	Total (mg AFDW)
Diurnal	Control	9 (2)	39 (17)	175 (14)	222 (11)
	S. La. Crude	16 (6)	21 (4)	85 (29)	122 (26)
	Wyo. Crude	24 (15)	38 (8)	128 (23)	189 (189)
Dark	Control	12	2	--	14
	S. La. Crude	12	4	--	16
	Wyo. Crude	41	25	--	66

Statistical significance (P = 0.95) for diurnal microcosms (* signifies significance)

	Water Column	Microcosm Sides	Sediment Surface	Total
Cont. vs. S. La. Crude	-	-	*	*
Cont. vs. Wyo. Crude	-	-	*	-
S. La. Crude vs. Wyo. Crude	-	*	-	*

[a]AFDW is Ash Free Dry Weight.
Values for diurnal microcosms are means from three replicates with standard deviations in parentheses.

Table 16. Biomass analyses and test results for statistically significant differences for the New Fork Lake microcosms.

Condition	Treatment	Water Column (mg AFDW*)	Microcosm Sides (mg AFDW)	Sediment Surface (mg AFDW)	Total (mg AFDW)
Diurnal	Control	14 (0)	36 (13)	1059 (476)	1108 (489)
	S. La. Crude	45 (10)	128 (82)	211 (87)	384 (15)
	Wyo. Crude	16 (6)	19 (4)	503 (68)	537 (66)
Dark	Control	6	14	--	19
	S. La. Crude	44	10	--	54
	Wyo. Crude	24	18	--	42

Statistical significance (P = 0.95) for diurnal microcosms (* signifies significance)

	Water Column	Microcosm Sides	Sediment Surface	Total
Cont. vs. S. La. Crude	*	-	-	-
Cont. vs. Wyo. Crude	-	-	-	-
S. La. Crude vs. Wyo. Crude	-	-	-	-

[a]AFDW is Ash Free Dry Weight.
Values for diurnal microcosms are means from two replicates with standard deviations in parentheses.

oiled treatments. Differences were statistically significant for comparisons between controls and both treatments in BL. No statistically significant differences existed in the NFL experiment even though the magnitude of mean differences between treatments and control were greater than in BL.

Total biomass was also consistently greater in diurnal controls than in treatments in both lakes. Additionally, biomass in WC treated microcosms was greater than SLC treated systems (statistically significant in BL). Also, the oiled treatments maintained in the dark had greater biomass accumulation than their unoiled counterpart for both lake experiments.

Table 17 contains biomass levels in NFL diurnal microcosms 20 days after oil was added. The only consistent difference between the control and treatments is that more biomass was contained in the water column of the latter. The total biomass at this intermediate date was much less than that on the final date in control microcosms but similar to that of the oiled treatments on the last day of the experiment.

Relative fluorescence. Relative fluorescence in the aqueous phase of diurnal BL microcosms is shown in Figure 34. Fluorescence was initially very low, but rapidly increased to a peak on day 17. Following that date fluorescence decreased in all microcosms during the next 17 days. It remained at a low level in control microcosms for the remainder of the experiment but increased in treatments after the addition of oil (fluorescence caused by oil was subtracted from total fluorescence to give the reported values). After another peak in treated microcosms on day 53 (11 days after oil addition), the fluorescence in these systems decreased to near control levels by the end of the experiment.

Bacteria. Aerobic, heterotrophic bacterial counts in the aqueous phase of BL microcosms are presented in Figure 35. Mean values and a statistical analysis of results are in Table 18. Prior to treatment, bacterial counts were similar for all microcosms under both diurnal and dark conditions. Seven days after treatment, the microcosms impacted with oil had higher bacterial population levels than controls, although the difference was not statistically significant. By the end of the experiment, statistically significant differences did exist between bacterial levels in control and treated diurnal microcosms. No significant difference existed between the oil types. Oiled

Table 17. Biomass analyses from various sites of New Fork Lake microcosms 20 days after oil was added.

Condition	Treatment	Water Column (mg AFDW*)	Microcosm Sides (mg AFDW)	Sediment Surface (mg AFDW)	Total (mg AFDW)
Diurnal	Control	19	42	232	294
	S. La. Crude	60	30	309	399
	Wyo. Crude	38	22	233	292

*AFDW is Ash Free Dry Weight.

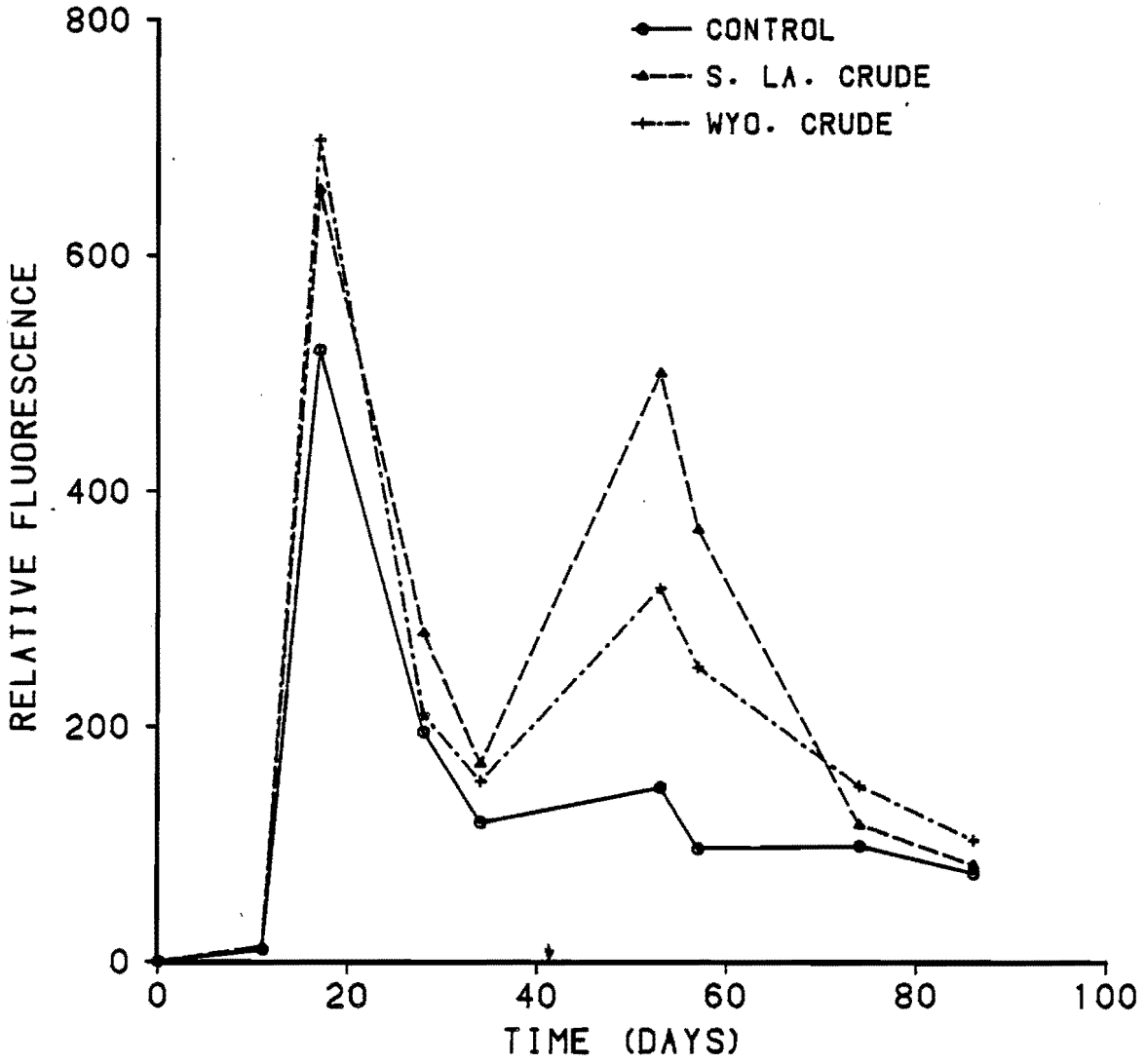


Figure 34. Relative fluorescence in the aqueous phase of Bear Lake microcosms.

microcosms maintained in the dark had higher bacterial populations than control microcosms.

Planktonic macroinvertebrates. Mean population levels of invertebrates sampled from the aqueous phase of BL microcosms are presented in Table 19. Chydorids were the major genera present; the only other animal sampled was a cyclopoid from a diurnal control microcosm on day 34. Mean population values were similar between treatment groups before treatment initiation. However, after oil was added, invertebrate populations sampled from the water column of oil impacted microcosms were zero on all dates whereas population levels in control microcosms remained fairly constant throughout the experiment. Thus, the apparent effect of both crude oils was to destroy the entire population of water column invertebrates in diurnal microcosms.

Invertebrate populations in the dark microcosms were very low or zero throughout the experiment.

Algal growth in microcosm medium. The response of the alga, S. capricornutum grown in medium taken from BL microcosms on day 90 of the microcosm experiment is shown in Figure 36.

Table 18. Mean values, standard deviations (in parentheses) and statistical comparisons of bacterial counts in Bear Lake microcosms.

Day	Diurnal			Dark		
	Control	S. La. Crude	Wyo. Crude	Control	S. La. Crude	Wyo. Crude
41	21,667 (15,526)	19,367 (7,021)	18,200 (7,366)	25,200	38,400	29,300
49	18,000 (9,035)	23,200 (17,032)	46,367 (26,046)	19,200	35,000	189,000
90	4,333 (2,122)	123,000 (69,846)	73,167 (30,436)	77,000	164,500	481,000

Statistical Comparisons for Diurnal Microcosms

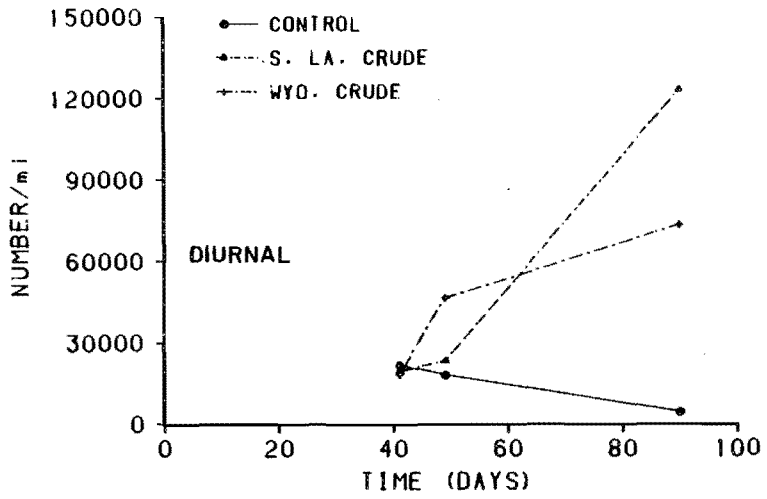
	Day 41	Day 49	Day 90
Control vs. S. La. Crude	-	-	*[a]
Control vs. Wyo. Crude	-	-	*
S. La. Crude vs Wyo. Crude	-	-	-

[a] * signifies statistical significance at P = 0.95.

Table 19. Invertebrates (all Chydorids) sampled from the aqueous phase of Bear Lake microcosms (mean values per liter are presented for diurnal microcosms with standard deviations in parentheses).

Day	Diurnal			Dark		
	Control	S. La. Crude	Wyo. Crude	Control	S. La. Crude	Wyo. Crude
34	55 (49)	56 (7)	51 (43)	1	5	3
38	47 (34)	67 (16)	106 (65)	3	2	0
50	32 (45)	0	0	0	0	0
52	73 (74)	0	0	0	0	0
72	39 (46)	0	0	0	0	0
86	30 (40)	0	0	0	0	0

Note: One cyclopoid was sampled in a diurnal control microcosm on day 34.



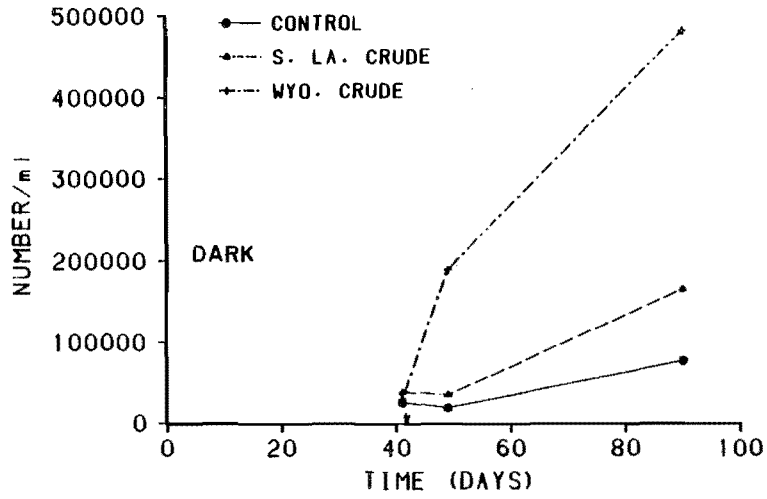
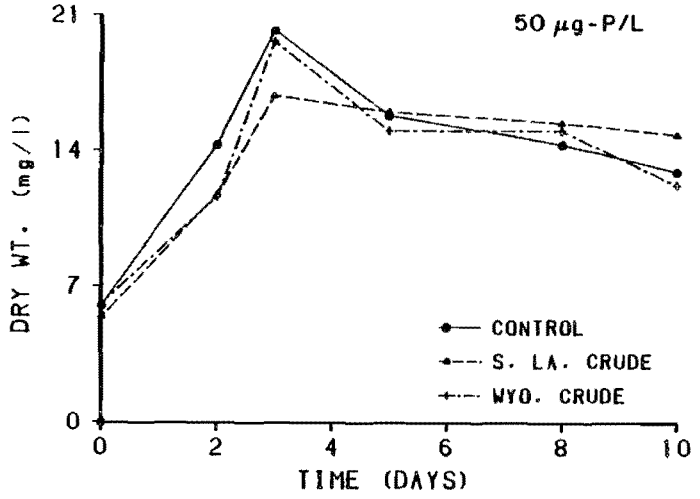


Figure 35. Bacterial population levels in Bear Lake microcosms.



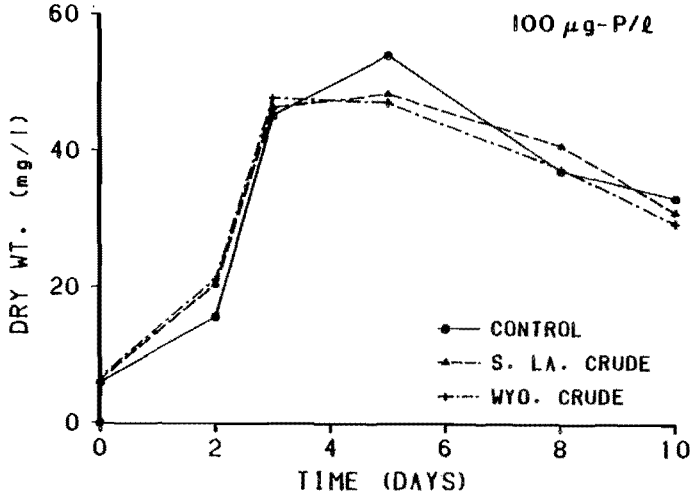


Figure 36. Growth response of Selenastrum capricornutum in the aqueous medium of Bear Lake microcosms.

Nitrogen and phosphorus were added to the medium to obtain concentrations of 485 µg/l and 50 µg/l, respectively, in one set of flasks, and 970 µg/l and 100 µg/l in the other. Under both nutrient conditions, all experimental units reached peak biomass during the initial 3 to 5 days. Significant differences do not exist between control or treatments. Thus, algal growth was not reduced when grown in medium taken for the oil-treated microcosms.

DISCUSSION

Gas Accumulation

Results of this portion of the research will be discussed in four parts. First, factors influencing mass balance results for gas data relevant to the interpretation of the microcosm data will be discussed. Second, effects of the crude oils on the relatively simple ecosystems maintained in darkness will be discussed. Interpretation of these data will aid in the analyses of data from the more complex diurnal ecosystems, which follows in the third section. Finally, comparisons between the water types and oil types involved in this study will be discussed.

Interpretation of the data collected on overall gas accumulation and the accumulations of specific gas species (e.g. O_2 and CO_2) in the microcosms is complicated by confounding factors. Four of these are discussed in this section.

First, in water with high alkalinity, such as that in Bear Lake, inorganic aqueous chemical reactions can have a major effect on the apparent production, or consumption, of carbon dioxide. Therefore, interpretation of biological activity based on CO_2 dynamics is tenuous. To illustrate this point, Table 20 contains calculated concentrations of aqueous CO_2 in Bear Lake and New Fork Lake media as functions of media pH. In the Bear Lake experiment, fresh medium was added to microcosms at an average pH of 7.8 while pH in the microcosms' aqueous phase reach levels as high as 8.5. There is a difference in equilibrium aqueous CO_2 concentration of 5.5 mg/l between those pH values in Bear Lake medium. Thus, a liter of fresh medium, when mixed with the microcosm's aqueous phase, could have released up to 5.5 mg/l CO_2 to the gaseous phase as a result of physical-chemical (as opposed to biological) mechanisms. This physical-chemical process may have been a major contributing mechanism to the net production of CO_2 and to the net production of total gas in Bear Lake microcosms (see Figures 28 and 30).

Physical-chemical release of CO_2 should not have been an important mechanism in the New Fork Lake microcosms because: 1) the maximum pH in New Fork Lake microcosms (7.5) was nearly that of fresh influent medium (7.3) and 2) New Fork Lake medium had a low alkalinity which reduces the potential for large quantities of CO_2 release due to physical-chemical mechanisms. A maximum of 0.64 mg/l CO_2 could have been released, and if the pH range was as in Bear Lake microcosms, only 0.44 mg/l CO_2 could have been released from New Fork Lake medium by physical-chemical mechanisms. Thus, a low alkalinity system permits more reliable interpretation of biogenic activity from CO_2 dynamics.

A second factor complicating the quantitative interpretation of net gas accumulation data is that many different biochemical compounds are produced (photosynthesized) and consumed (respired) in aquatic systems (Ryther 1956; Odum 1971). If only carbohydrates were involved, the following equations would describe gas dynamics:

$$6\ CO_2 + 6\ H_2O \rightarrow C_6H_{12}O_6 + 6\ O_2 \quad \text{(photosynthesis)} \quad . \ . \ . \quad (10)$$

$$6\ O_2 + C_6H_{12}O_6 \rightarrow 6\ CO_2 + 6\ H_2O \quad \text{(respiration)} \quad . \ . \ . \ . \quad (11)$$

Table 20. Calculated concentrations of aqueous carbon dioxide (mg/l H_2CO_3* as CO_2 at 760 mm Hg and 298 K) in Bear and New Fork Lake media as a function of media pH.

pH	Bear Lake Medium	New Fork Lake Medium
7.0	43.9 mg/l	3.47 mg/l
7.3	22.0	1.74
7.4	17.5	1.38
7.5	13.9	1.10
7.6	11.0	0.87
7.7	8.7	0.69
7.8	6.9	0.55
7.9	5.5	0.44
8.0	4.4	0.34
8.1	3.5	0.27
8.2	2.7	0.22
8.3	2.2	0.17
8.4	1.7	0.14
8.5	1.4	0.11

The net accumulation of total gas due to biological activity would be zero, and molar quantities of glucose production or respiration could be assessed by changes in molar quantities of CO_2 and O_2. However, biochemical compounds more highly reduced than carbohydrates (e.g., proteins and fats) are involved and greater molar quantities of O_2 are released during plant production than molar quantities of CO_2 consumed. Furthermore, the ratio "O_2 released:CO_2 consumed" (termed photosynthetic quotient or PQ) depends on the nitrogen species being used by the plant. Growing plants assimilate reduced forms of nitrogen; if an oxidized form is available (e.g., NO_3), the plant converts it to a reduced form (e.g. NH_3) during assimilation with a concomitant release of O_2. Thus, the PQ is higher if NO_3, rather than NH_3, is used (Ryther 1956).

As a result of the different biochemical species produced and different forms of nitrogen assimilated, PQs in the range of 1.0 to 1.75 have been reported (Odum 1971). Thus a net gas accumulation versus time function with a slope of zero might be interpreted identically, in terms of net plant production, to one with a slope of 0.75, depending on plant species involved, biochemical composition of the plant, and nutrient conditions. The consumption of oxygen per molar quantity of CO_2 released during respiration is likewise dependent on the biochemical species being oxidized. More highly reduced compounds have higher O_2 consumed:CO_2 released ratios. Therefore, direct comparisons of net gas production, or consumption, between microcosms assumes similar biochemical components and nutrient conditions.

Ecosystems with positive net production accumulate gases since formation of more highly reduced biochemical compounds (e.g. proteins and fats) liberate higher molar volumes of O_2 than molar volumes of CO_2 consumed. Thus, past microcosm studies have

correctly used the criterion of net gas production as an indicator of actively producing ecosystems (Porcella et al. 1975; Medine 1979). However, quantitative statements or reliable comparisons between microcosms cannot be based on that criterion unless one knows the biochemical species being produced and consumed in the various microcosms.

Another factor complicating the interpretation of gas production results from the addition of highly reduced hydrocarbons to the treatment microcosms. Oxygen is consumed during the initial stages of hydrocarbon biodegradation without a concurrent release of CO_2 (Gaudy and Gaudy 1980; Hansen and Kallio 1957). A number of intermediate steps can be involved in the ultimate biological breakdown of the hydrocarbons, each producing a more highly oxidized compound, but not necessarily resulting in CO_2 release. The net result of hydrocarbon degradation is a reduction in gas volume, but the interpretation of the reduction is different than that in a system without hydrocarbons.

The final confounding factor associated with interpreting gas accumulation or consumption within the microcosms is the inhibition of gaseous diffusion across the gas-water interface by an oil coating. Table 21 documents the oxygen diffusion inhibition. Tabulated values are based on dissolved oxygen measured in the microcosms' aqueous phase (Figures 15 and 16), oxygen levels in microcosms' gaseous phase (Figures 19 and 20) and discrepancies between these two based on Henry's Law. Surface active agents, such as petroleum hydrocarbons, are known to restrict gaseous diffusion by forming a physical barrier at the air-water interface (Mancy and Okun 1965). The effect was greatest in dark New Fork Lake microcosm treated with oil, where the oxygen utilization rate was highest, no photosynthesis was replenishing the oxygen supply, and the oil film restricted oxygen diffusion.

Oxygen diffusion was inhibited by oil over the long-term (48 days) even though continuous stirring occurred 2 to 3 cm below the air-water interface. In lakes, or sheltered portions of lakes, the reduction of oxygen diffusion due to an oil spill would aggravate low oxygen conditions caused by hydrocarbon oxidation. Detrimental effects on the lakes biota and the release of reduced

Table 21. Measured dissolved oxygen concentration (percent) in the microcosms' aqueous phase relative to concentration expected based on Henry's Law.

Lake	Treatment	Diurnal		Dark	
		Before Treatment	After Treatment	Before Treatment	After Treatment
Bear	Control	104	108	107	104
	S. La. Crude	104	94	107	60
	Wyo. Crude	104	86	106	66
New Fork	Control	110	104	101	95
	S. La. Crude	107	82	100	54
	Wyo. Crude	111	80	103	49

compounds from the sediments (Mortimer 1941, 1942) could result.

Because of insufficient information to deal quantitatively with those complicating factors, total gas and CO_2 production will not be intrepreted in a quantitative sense in later sections. Interpretation of oxygen dynamics is also complicated by different biochemical and nutrient conditions among the microcosms. However, the fact that oxygen dynamics are directly related to biological activity permits conclusions on the effect of oil from information on oxygen consumption or production. Therefore, oxygen dynamics will be discussed in quantitative terms. However, due to inhibition of O_2 diffusion by the oil film, the quantities presented are less than the actual effects when the discussion deals with gaseous phase oxygen level, or net oxygen accumulation values, but greater when discussing aqueous oxygen levels.

Dark Microcosms

The experimentation with microcosms maintained in total darkness will be discussed before the diurnal microcosms for two reasons. First, results from dark microcosms are more easily interpreted because they contained a "simple" biological community whose only function was respiration (photosynthesis also occurred in the diurnal systems). Second, an understanding of phenomena occurring in the dark microcosms aids in data interpretation for the diurnal systems.

Respiration

Perhaps the major effect of oil addition to the dark microcosms was to drastically increase the rate of oxygen consumption by the decomposer community. The effect of increased oxygen consumption on oxygen levels in the aqueous and gaseous phases of treated microcosms can be seen in Figures 15 and 19 for Bear Lake and Figures 16 and 20 for New Fork Lake. The effect of the oil is immediate, as indicated by the drop in oxygen level following oil addition; apparently, the overall decomposer community quickly acclimated to the petroleum hydrocarbons and began to oxidize them. Dissolved oxygen levels became very low by the end of both experiments; 1.1 mg/l in Bear Lake and 0.4 to 0.7 in New Fork Lake.

Low oxygen conditions in the New Fork Lake oiled systems actually destroyed the oxidized microzone within the sediments by day 60 (18 days after oil addition) and large amounts of inorganic phosphorus were released from the sediments (Figure 11). A very distinct rust color appeared in the aqueous phase of oiled microcosms at this time due to the influx of soluble ferrous iron (Appendix L) from the sediments (Mortimer 1941, 1942). Inorganic phosphorus reached peak concentrations (up to 228 $\mu g/\ell$) by day 80 then decreased by day 90. Between those dates, an iron floc formed and apparently swept inorganic phosphorus from the water column as the floc precipitated. Inorganic phosphorus was not released from sediments of the New Fork Lake control microcosms during the experiment.

Bear Lake treated microcosms reached low oxygen levels (1.1 mg/l as opposed to 6.0 mg/l for the control), but reduced compounds were not released from the sediments. It is very likely that the destruction of the oxidized microzone would have occurred if the experiment had extended beyond 90 days since a constant rate of oxygen decrease (0.3 to 0.4 mg/l-10 d) had been occurring during the final 40 days of the experiment. Destruction of the oxidized microzone in New Fork Lake microcosms occurred when dissolved oxygen of the aqueous phase fell below 1.0 mg/l.

Low oxygen levels in aquatic ecosystems have several deleterious effects. First, as demonstrated by the New Fork Lake experiment, reduced compounds and nutrients can be released

from the sediments. The reduced compounds are often harmful to aquatic organisms, and the influx of nutrients can alter the trophic status of the lake. For example, if phosphorus was released to New Fork Lake to the extent that it was released in this experiment the lake's oligotrophic status would almost certainly be lost. Second, low oxygen conditions are detrimental to aquatic life even without the influx of toxic reduced compounds. Generally, highly desirable species (e.g. mayflies, trout) succumb to low oxygen conditions before less desirable organisms. Third, as dissolved oxygen drops below 2 mg/l, biochemical oxidation rates are reduced (e.g., Metcalf and Eddy 1979). Furthermore, petroleum hydrocarbons cannot be biologically degraded under anaerobic conditions (Gaudy and Gaudy 1980; Hansen and Kallio 1957). Anaerobic conditions first occur at the sediment-water interface where hydrocarbons tend to accumulate due to their affinity for sediment particles (Zürcher and Thüer 1978; Knap and Williams 1982; Gearing et al. 1980). Therefore, the effects of oil pollution are prolonged by low oxygen conditions in aquatic ecosystems because hydrocarbon degradation is slowed. Positive feedback accentuates the problem as the hydrocarbons contribute to low oxygen conditions. Thus, severe environmental damage could potentially result from a single oil spill.

Rates of oxygen utilization in the dark microcosms, before and after oil addition, are listed in Table 22. For each set of microcosms, the rates were similar before oil treatment. New Fork Lake systems used oxygen at a higher rate than Bear Lake systems during this initial phase, presumably because New Fork Lake sediment contained more organic matter than Bear Lake sediments (1.4 percent versus 1.1 percent). After oil was added, oxygen utilization increased much more in the Bear Lake microcosms than in New Fork Lake microcosms. Bear Lake treatments consumed oxygen at a rate 16.5 times that of controls while New Fork Lake rates were increased only 1.3 times due to oil. The effect of oil in Bear Lake microcosms is more realistic than that in New Fork Lake microcosms; prior low oxygen conditions in New Fork Lake microcosms probably reduced the rate of hydrocarbon oxidation. Dissolved oxygen levels quickly dropped from about 5.4 to

Table 22. Oxygen utilization rates in dark microcosms before and after oil addition.

Lake	Treatment	Oxygen Utilization Rate (mg/m^2-d)	
		Before Oil Addition	After Oil Addition
Bear	Control	79[a]	24[b]
	S. La. Crude	109	371
	Wyo. Crude	101	420
New Fork	Control	203	303[b]
	S. La. Crude	221	418
	Wyo. Crude	203	381

[a]These were pretreatment values for the microcosms.
[b]No oil was added to controls.

1.0 mg/l during the 3 weeks immediately following oil addition, but then remained at about 1 mg/l for the next 3 weeks. Apparently, 1 mg/l of dissolved oxygen was a critical level, below which hydrocarbon oxidation essentially ceased.

Based on results from Bear Lake microcosms complete anaerobic conditions would result in about 20 days if oil were spilled at the areal dosage of these experiments (0.212 ℓ/m^2) in water 1 meter deep if oxygen input (i.e., atmospheric diffusion, photosynthesis) did not occur. Conditions necessary for the above are unrealistic for natural lakes, but the example illustrates a "worst case" situation. Habitats approaching the above conditions are found in sheltered littoral zones with a thick covering of emergent vegetation, or a marsh.

Nutrient immobilization

Nitrate concentrations in oil-treated dark microcosms were consistently lower than those in control systems (Figures 13 and 14). It is very likely that the decomposer populations were immobilizing that nutrient as they oxidized petroleum hydrocarbons, which offer a rich source of organic carbon but extremely low concentrations of nitrogen and phosphorus (Pancirov 1974). The amount of inorganic nitrate accumulated in the aqueous phase of dark microcosms is shown in Figures 26 and 27 for the Bear Lake and New Fork Lake microcosms respectively. It is clear that more nitrate was immobilized in oil-impacted microcosms than in their unoiled counterparts for both experimental lakes.

Nutrient immobilization by heterotrophic populations due to oil pollution has an environmental significance for natural ecosystems. Microbial heterotrophic communities are superior to autotrophs as competitors for limiting nutrients in aquatic ecosystems because of their small size (high surface to volume ratio) and rapid growth rate (Rigler 1956). Severe nutrient limitation to higher plants might result from oil pollution, especially in oligotrophic aquatic ecosystems. Under normal conditions, actively growing plants produce oxygen which helps offset oxygen consumption by heterotrophs. In the case of oil pollution not only is there greater consumption of oxygen by heterotrophs, but oxygen production by plants could be decreased because of greater nutrient limitation. The overall impact is an imbalance in terms of autotrophic versus heterotrophic activity.

A high degree of inorganic phosphorus immobilization occurred in oiled-Bear Lake microcosms (Figure 26). However, phosphorus was released in New Fork Lake oil-treated microcosms (Figure 27). The phosphorus release resulted from low oxygen conditions as discussed above.

Biological biomass

Total biomass estimates for dark, oil treated microcosms' sides and water column were, on the average, 3 and 2.5 times higher than controls in Bear Lake and New Fork Lake respectively (Tables 15 and 16). Bacterial counts were from 2.1 to 6.3 times higher for SLC and WC treatments than for controls in BL microcosm, suggesting that at least some of the biomass increase in oil treated microcosms was due to higher bacteria standing crops. Higher biomass in the oil treatments supports the finding of increased biological activity of the heterotrophic community due to the crude oil.

Diurnal Microcosms

Oxygen dynamics

In diurnal microcosms, as in the dark systems, dissolved oxygen in the aqueous phase and the mole fraction of oxygen in the gaseous phase decreased immediately following oil addition

(Figures 15 and 19 for BL microcosms and Figures 16 and 20 for NFL microcosms). The responses of the biological community to oil addition were both immediate and long-term. Dissolved oxygen continued to be reduced at roughly a constant rate (except near the experiment's end in NFL microcosms treated with SLC) for the entire experiment after oil addition. Dissolved oxygen concentrations dropped to between 3.3 to 4.7 mg/l in BL microcosms and 2.0 to 2.6 in NFL microcosms even though oxygen was added via photosynthesis and in the fresh medium (approximately 8 mg/l every other day). For comparison, control microcosms reach dissolved oxygen concentrations of 9.2 in BL microcosms and 10.0 in NFL microcosms.

The immediate reduction of oxygen in treated microcosms indicates a rapid acclimation of heterotrophic communities to the influx of petroleum hydrocarbons. In the dark systems, no oil toxicity to the overall heterotrophic activity in these experiments was observed.

Low dissolved oxygen in treated NFL microcosms caused reducing conditions which resulted in the destruction of the oxidized microzone. Sediment release of inorganic phosphorus to the microcosms aqueous phase by day 70 occurred in the experiment. A rust color, due to iron (Appendix L), was imparted to the microcosms' aqueous phase as also occurred in NFL dark oil-treated microcosms. Phosphorus concentrations did not reach as high levels in diurnal NFL microcosms as in the dark microcosms; but this may have been because less severe reducing conditions occurred in diurnal systems or because nutrient uptake by both autotrophs and heterotrophs was taking place.

Mean rates at which oxygen was produced or consumed in diurnal microcosms are given in Table 23. Before treatment initiation, all three groups of microcosms within a lake had similar oxygen production rates. NFL microcosms had much higher production rates during this initial phase than BL microcosms; possible reasons are higher nutrient release rates from NFL microcosm sediment and the coprecipitation of inorganic phosphorus with $CaCO_3$ in BL microcosms. Mass balance calculations

Table 23. Oxygen production (negative values indicate oxygen consumption) rates for diurnal microcosms before and after oil addition.

Lake	Treatment	Oxygen Production Rate (mg/m^2-d)	
		Before Oil[a] Addition	After Oil Addition
Bear	Control	45	54[b]
	S. La. Crude	41	-242
	Wyo. Crude	62	-296
New Fork	Control	309	72[b]
	S. La. Crude	268	-304
	Wyo. Crude	280	-457

BL values are based on three replicates and NFL on two replicates.

[a]These were pretreatment values for the microcosms.
[b]No oil was added to controls.

indicate an average of 670 mg of $CaCO_3$ precipitated from control BL microcosm aqueous phase during the experiment, and Figure 9 shows pH levels were high enough throughout most of the experiment (up to 8.5) to cause $CaCO_3$ precipitation in water with high alkalinity, such as the BL medium (265 mg/l as $CaCO_3$).

Following oil addition, treated microcosms consumed oxygen as demonstrated by the negative slopes on the oxygen accumulation curves (Figures 30 and 31). In contrast net production continued in control microcosms throughout the remainder of the experiment. The key fact illustrated by these data is that crude oil caused the ecosystems to become heterotrophically dominated. Potential reasons for heterotrophic domination are 1) toxic effects of crude oil inhibited plant growth and 2) increased organic loading (petroleum hydrocarbons) caused increased nutrient limitation to autotrophs as a result of nutrient competition from competitively superior bacteria. These potential explanations are analyzed in a later section.

Oxygen consumption rates were higher for NFL microcosms treated with oil than for their BL counterparts (1.3 times for SLC and 1.5 for WC). NFL microcosms were more productive prior to oil addition (Figure 31), and at least some of the accumulated biomass was available for heterotrophic oxidation following oil addition.

Oxygen consumption rates for systems treated with WC were greater than for those treated with SLC (1.2 times in BL microcosms and 1.5 in NFL microcosms), possibly because components of WC were more readily susceptible to rapid oxidation than SLC or because more plant biomass was initially destroyed by WC than SLC and that additional dead biomass increased the detritus pool in microcosms treated with WC. Information is not available to determine the magnitude of these potential effects.

Biomass

Biomass data were generally variable among microcosms for statistically significant differences between controls and treatments to be detected. However, clear patterns existed (Tables 15 and 16) and these will be discussed. Total biomass was consistently higher in control microcosms than in their oil-treated counterparts. This difference was mainly due to more biomass on the sediment surface, which was the major biomass component in all microcosms. Plants at the sediment surface were primarily macrophytes and filamentous algae with long life cycles and low turn over rates. Crude oil proved particularly detrimental to these plants and recovery was slow after initial toxic effects of the oil subsided. Biomass in the water column, which is dominated by rapidly growing planktonic species with short life cycles, was generally higher for oil treated microcosms. Recovery of these plants was more rapid after the initial toxic effects of crude oil had subsided. Biomass on the microcosm sides displayed no consistent differences between oil treated and control microcosms.

Planktonic invertebrates in BL microcosms, composed mostly of Chydorid sp., were completely destroyed by the crude oils (Table 19). No tests were made to determine how long the oil would have had to weather before invertebrates could have survived if reinstated. In natural ecosystems planktonic invertebrate populations are frequently totally destroyed by an oil spill in a local region. However, new populations of planktonic invertebrates often migrate to, and become established in, the affected region within weeks of a spill (Hyland and Schneider 1976). Thus, the observations that planktonic animals were absent for the entire experiment following oil addition may over estimate the impact of the oil, since reinoculation via migration was excluded.

Nutrients

Analysis of nutrient data does not lead to significant conclusions concerning the effects of crude oil on the diurnal microcosms. Since both photosynthesis and respiration were occurring, nutrient data analysis was unproductive. Basically, the microcosms were phosphorus limited, and that nutrient reached low concentrations by day 20 in all diurnal microcosms. Inorganic phosphorus remained at low levels in control and treatments alike throughout the experiment in the BL microcosms due to a combination of primary production and decomposition. Similarly, significant differences between treatments and control microcosms did not exist for nitrate, nitrite, or ammonia in BL microcosms (Figure 13 and Appendix D). Parameters other than nutrient concentration (e.g. oxygen production and consumption) were more useful in determining whether primary production or respiration dominated in particular microcosms.

A greater concentration of inorganic phosphorus in NFL oil-treated microcosms from days 70 through 90 did distinguish treatments from controls in that experiment (Figure 12). In the dark NFL microcosms, low oxygen conditions lead to reducing conditions that destroyed the oxidized microzone within the sediments. Concentrations of inorganic phosphorus increased in the aqueous phase of the treatment microcosms, and iron was released (Appendix L). It is significant that oxygen conditions were sufficiently low to cause reduced compounds to be released from the sediments even in microcosms in which photosynthetic oxygen was being produced. Thus, dangerously low oxygen conditions could result following an oil spill even during a season and in a place where primary production is occurring.

Oil toxicity versus nutrient immobilization

In this section the relative importance of oil toxicity and nutrient immobilization will be discussed relevant to crude oil mediated impacts on the microcosms' ecosystem. Bioassay experiments (Figures 4-7) and initial responses of plants in the microcosm experiments (Appendix E) clearly show that fresh, unweathered oil is toxic to plants. Other studies collaborate immediate toxicity of fresh crude oil to aquatic plants (Kauss and Hutchinson 1975; Atlas et al. 1978). Thus, considerable evidence supports that fresh crude oil can be very destructive to plant communities.

Marine and freshwater studies have shown that overall bacterial populations are often stimulated by crude oil (Lock et al. 1981a, 1981b; Steward and Mark 1978; Atlas et al. 1978) although some bacterial groups are inhibited (Colwell et al. 1978; Walker et al. 1975; Hodson et al. 1977; Walker and Colwell 1974).

The study support those findings, overall decomposer communities were apparently not adversely affected by crude oil. Oxygen consumption, an index of heterotrophic activity, increased immediately following oil injection (Figures 30 and 31). In addition, bacterial numbers increased in oil treated BL microcosms (this was not assessed in NFL microcosms) and the overall biomass in dark oil-treated microcosms was greater than that in their control counterparts.

Increased heterotrophic activity immobilizes nutrients when an organic substrate is being oxidized that is low in critical nutrients such as nitrogen and phosphorus (Gaudy and Gaudy 1980). Crude oil is such an organic substrate

(Pancirov 1974). This nutrient immobilization by the decomposers of the crude oil is shown in Figure 26 for nitrate and orthophosphate in BL microcosms and in Figure 27 for nitrate in NFL microcosms. As long as petroleum hydrocarbons were being biologically degraded in these systems, nutrients would be continuously immobilized. Throughout the period following oil addition in these studies (48 d) there was a relatively constant rate of oxygen utilization in all microcosms, indicating a phase of nutrient immobolization of at least that long, and probably much longer, in systems exposed to oil. Thus, nutrient immobilization by heterotrophs can limit nutrients availability to autotrophs, and this phenomenon can have major long-term disruptive effects in aquatic systems.

Three factors support the hypothesis that nutrient immobolization, rather than direct toxic effects of crude oil on plants, was the major effect causing a heterotrophically dominated ecosystem in oil-treated microcosms. First, the relative fluorescence (an index of chlorophyll) actually increased in the BL oil-treated microcosms following oil addition (Figure 34). The autotrophs accounted for in this measurement would be small organisms with short life cycles. Thus, they could compete with bacteria for nutrients more easily than larger plants because of their high surface to volume ratios. Furthermore their short life cycles permit quicker recovery after the initial toxic effects of the crude oil subsides. The increase in planktonic algal population in oil-treated microcosms may have been a result of nutrients being released from organisms destroyed by toxic effects of the oil (Gordon and Prouse 1973). It is conceivable that excess nutrients could have been available for a short time following the incidence of oil pollution (enough time for a planktonic algal population to increase) before severe nutrient limitation occurred. Notice, the planktonic algal population decreased to near control levels 20 days after their initial increase in BL microcosms (Figure 34). The key point is that planktonic algal populations increased in oil-treated microcosms within 11 days after oil addition, thus initial toxic effects to that overall plant community was short-lived.

The second piece of evidence resulted when inorganic phosphorus was released from sediments to the water column in NFL treated microcosms. A visually observed "greening up" indicated a more healthy and actively growing plant community (Appendix E). By the end of the experiment, some microcosms had experienced an increased oxygen concentration in their aqueous phase due to autotrophic production (Appendix D and Figure 15). Apparently, the plant community responded to increased levels of critical nutrients, and overall restriction of growth due to the oil did not occur.

Thirdly, by increasing nutrients in the aqueous phase of BL microcosms following that experiment and observing the growth of S. capricornutum in the resulting medium, it was apparent that compounds restricting growth to that alga were not present in the oil treatments following 48 days of oil weathering (Figure 36). Neither the log phase of growth, nor overall biomass achieved, was affected by the weathered oil at two nutrient levels.

Overall, the above evidence indicates that even though toxic effects of crude oils are very detrimental to plant growth initially, their toxic impact is diminished quickly. Over the long-term the increased dominance of heterotrophic populations and overall restriction of photosynthetic communities following oil addition (Tables 16 and 17) due to nutrient immobilization by crude oil-simulated decomposer populations were the primary environmental impact.

Comparisons Between Lake Water Types and Oil Types

Comparisons between the BL and NFL microcosm experiments were not decisive in demonstrating different responses, due to soft versus hard water systems, to oil pollution. The most notable difference between the two microcosm experiments was a greater rate of oxygen consumption in NFL diurnal systems, but that difference cannot be attributed to water hardness. NFL sediments had a higher organic content than BL sediments, hence even unoiled dark NFL microcosms had higher oxygen consumption rates than their BL counterpart. Greater net primary production (therefore greater plant biomass accumulation) had occurred in diurnal NFL microcosms than BL microcosms by the time of oil addition; thus, the greater oxygen consumption rate of the former after oil addition was, at least, partially due to greater input of dead plant biomass into the detrital pool. In addition, a different plant community which likely had a different degree of susceptibility to crude oil toxicity developed in the two sets of microcosms. Even if the response of the plant community to crude oil had been tested in the two experiments, potential differences could have been due to differences of the plant community or differences in water chemistry.

The objective of this research was to simulate the natural ecosystem of BL and NFL as closely as possible in the microcosm experiment, hence sediments and inocula from the respective lakes were used. To test differences in oil responses between hard and soft water, it would be necessary to use a common sediment and inoculum of biotic components in microcosm experiments with water hardness as the only variable.

Differences in responses of the biological community of the microcosm to the two crude oils were generally not substantiated by statistical analyses. Visual observations, and to some extent quantitative results, suggest that WC may have had greater toxic effects and exerted a higher oxygen demand than SLC, although there were exceptions.

In general, responses to oil pollution were similar regardless of the lake being simulated or the crude oil used. Increased oxygen demand, nutrient immobilization, reduction in plant biomass accumulation and a heterotrophically dominated biological community resulted in all lake-oil type combinations.

CONCLUSIONS

Responses of the Bear and New Fork Lake environments to impacts of South Louisiana (SLC) and Wyoming Crude (WC) oils were simulated in gas-aqueous-sediment microcosms. The following conclusions are based on results of these studies:

1. Direct addition of from 0.08 to 2.8 ml/l crude oil reduced the maximum growth rate and standing crop of S. capricornutum in modified bioassay tests. Furthermore, increasing concentrations of the oils increased their deleterious effects.

2. Addition of the suspended fraction of crude oils decreased the maximum standing crop, and in some cases maximum growth rate, of S. capricornutum, but not to the extent of directly added oil.

3. Although all suspended oil bioassay treatments adversely affected S. capricornutum's growth response, differences in oil dosages had little effect. Apparently, the dissolved hydrocarbon concentrations at the lowest initial oil dosage used (1.0 ml/l) were nearly as detrimental as those concentrations at the highest dosage (20 ml/l).

4. WC had greater effects than SLC in 14 day bioassay tests at a given oil concentration.

5. Fresh crude oil was toxic to plants but not to overall decomposer communities.

6. Increased rates of net oxygen consumption occurred within 8 days after oil addition in all microcosms.

   a. Elevated rates of net oxygen consumption persisted in oiled microcosms for the 48 days that measurements were taken.

   b. The rate of net oxygen consumption was constant, in all but NFL dark microcosms, throughout the oil impacted portion of the microcosm experiment. The effect of oil on oxygen demand was not diminished for the initial 48-day period after its addition.

   c. The rate of oxygen consumption in NFL dark microcosms treated with oil was constant until oxygen concentrations dropped to approximately 1 mg/l, at which time the rate declined. Biooxidation of oil was apparently reduced or even stopped under low oxygen conditions.

   d. Based on oxygen utilization rate in BL dark oiled microcosms, oxygen depletion would occur in approximately 20 days if an affected lake area 1 meter deep was initially saturated with oxygen, and had no additional oxygen input.

   e. Positive oxygen production occurred in all control diurnal microcosms throughout the 90 day experiments, but net oxygen consumption began within 8 days after oil addition to diurnal microcosms.

7. Strictly quantitative interpretation of total gas and CO_2 production (or consumption) within the microcosms was confounded by inorganic aqueous chemical reactions, biochemical compounds involved in photosynthesis or respiration, the multistep process of petroleum hydrocarbon oxidation and gaseous diffusion inhibition by the

crude oil film at the microcosms aqueous phase surface. The aqueous phase of oiled microcosms was up to 51 percent under saturated relative to the gaseous phase over a 48 day period due to restriction of gaseous diffusion caused by the oil film.

8. Iron and phosphorus were released from sediments in NFL oiled microcosms because of low oxygen conditions caused by the oil.

9. Nitrogen and phosphorus were immobilized in dark, oiled BL microcosms as the nutrient poor crude oil was being biologically oxidized.

a. Nitrogen was immobilized in dark, oiled NFL microcosms but this situation with respect to phosphorus could not be determined because of inputs of sediment phosphorus.

b. Primary production and decomposition were both occurring in diurnal microcosms so the extent that nutrients were immobilized by oil oxidizing heterotrophs could not be directly determined.

10. Overall biomass in dark, oiled microcosms was 2.5 to 3.0 times that in unoiled systems. Bacteria numbers were 2.1 to 6.3 times higher in dark, oiled microcosms than their unoiled counterparts.

11. Biomass accumulation, primarily composed of autotrophs, was curtailed by oil addition to diurnal microcosms.

a. The site of greatest biomass reduction by oil in diurnal microcosms was the sediment surface, where plants with long life cycles and slow growth rates, such as macrophytes and filamentous algae, were dominant.

b. Algal biomass in the open water column was increased within 11 days after oil addition to BL microcosms.

c. Planktonic biomass was greater in oiled microcosms (both BL and NFL systems) by day 90 of the experiment.

12. Based on samples which were 10 percent of the total microcosm volume, populations of invertebrates, Chydorids spp., were completely and immediately destroyed in BL microcosms by oil addition.

13. Growth of S. capricornutum was unaffected by the weathered oil fraction in the BL aqueous phase following that microcosm experiment.

14. All evidence supports the hypothesis that the increased availability of an organic substrate to the decomposers and nutrient limitation to plants which was increased by nutrient immobilization by oil-decomposers, rather than toxic effects of crude oil on plants, were the major factors leading to the long-term heterotrophically dominated ecosystem following oil addition.

15. Increased oxygen demand, nutrient immobilization, reduction in plant biomass accumulation, and a heterotrophically dominated biological community were common results of oil addition to all experimental lake-oil type combinations.

PART II

EFFECTS OF CRUDE OILS ON AQUATIC PLANT LITTER DECOMPOSITION

METHODS AND MATERIALS

Field Experiment

This portion of the study was performed to assess environmental consequences of crude oils on the decomposition of autochthonous plant litter in the littoral zones of Bear Lake (BL) and New Fork Lake (NFL). In the event of an oil spill on a lake, littoral zones could be affected to a great extent because of wind transport of the slick to those zones, and adherence of oil to surfaces, such as vegetation. For this reason, and because littoral plant decomposition is an important function in lakes, this decomposition study is relevant to the assessment of impacts that could affect a lake following an oil spill.

The site for the in situ decomposition study at BL was in the littoral region directly east of the Utah State Limnology Laboratory. Plant litter substrates were anchored in approximately 2.5 m of water on July 29, 1980. A drop in water level during the experiment necessitated movement of the substrates to a deeper site approximately 100 m to the east of the original site on day 115 of the experiment. The minimum measured water depth over the substrates was 1.5 m. A description of the Bear Lake study site is given in Table 24.

The NFL study site was approximately 150 m offshore of the United States National Forest Service boat ramp on the northwest shore. Plant litter substrates were anchored on August 14, 1980, in 2.5 m of water; the water depth increased to 3 meters during spring runoff (June 1981). Additional information on the NFL site is found in Table 24.

The experimental design included two oil treatments and a control for each of two plant litter types and two lakes. Destructive sampling, with three replicates per treatment, was performed nine times in each lake. Sampling dates and lake temperatures are listed in Table 25.

Plant litter used for this study in both lakes was obtained from fresh Typha

Table 24. Characteristics of decomposition study sites for Bear and New Fork Lakes.

	Bear Lake	New Fork Lake
Sediment Type	Sandy and unconsolidated	Clayey and matted together with roots and other organic debris
Macrophytes Present	Potamogeton sp. Rununculus sp.	Elodia sp. Potamogeton spp. Rununculus sp. Myriophyllum sp.
Percent Cover	7.2 (S_d = 5.0, n = 7)	61.9 (S_d = 15.8, n = 9)

Table 25. Sampling dates and lake temperatures for litter decomposition study.

Bear Lake			New Fork Lake		
Date	Temp. °C	Day of Experiment	Date	Temp. °C	Day of Experiment
July 30, 1980	22	0	Aug. 14, 1980	16	0
Aug. 2	22	3	Aug. 17	16	3
Aug. 6	20	7	Aug. 21	16	7
Aug. 13	19	14	Aug. 28	15	14
Aug. 27	17	28	Sep. 11	14	28
Sep. 23	15	55	Oct. 9	11	56
Nov. 21	7	114	Nov. 24	5	102
Mar. 23, 1981	5	236	May 8, 1981	5	267
June 16	13	321	June 24	14	314
July 30	23	365	Aug. 14	18	365

latifolia (common cattail) and Potamogeton foliosus (pond weed). T. latifolia was collected from a small marsh near the Bear Lake Utah State Boat Marina. P. foliosus was collected from the Wellsville Reservoir near the stream outlet. After collecting the T. latifolia litter it was immediately cut into 8-10 cm sections. Both litter types were allowed to air dry; one day for P. foliosus and two days for T. latifolia. Following the air drying, the plant litter was separated into quantities of approximately 25 g for T. latifolia and 6 g for P. foliosus and then weighed to the nearest 0.1 mg. The preweighed litter was sewn into 15 by 15 cm fiber glass litter bags with a 1.5 mm mesh size (Bobcock and Gilbert 1957). Additional litter samples were weighed, oven dried at 80°C for 24 hours, and reweighed to obtain data for an air-dried to oven-dried regression so data could be converted to an oven-dried basis.

Treatments were established by submerging one-third of the prepared

litter bags for each plant species into either South Louisiana Crude (SLC) or Wyoming Crude (WC). Excess oil was allowed to drain from the litter for 24 hours. The plant litter bags were maintained at 5°C while being transported to the field study sites where they were anchored to begin the experiment.

On each sampling date, individual litter bags were placed into 0.95 ℓ mason jars filled with ambient lake water to determine oxygen consumption rates by the decomposer community associated with the litter. The jars were then firmly sealed and incubated in the dark at ambient lake temperatures for 3.5 to 4.5 hours. Following incubation, water was siphoned from the individual mason jars into 300 ml dissolved oxygen bottles, and dissolved oxygen contents were determined by the Winkler Azide method (APHA 1980). Four to six mason jars were simultaneously filled with lake water to serve as respiration controls.

Following determination of the dissolved oxygen utilization rates, plant litter was removed from the litter bags and oven dried at 80°C for 40-48 hours. The litter mass was then weighed to 0.1 mg. A subsample (about 1 gram) was reweighed and submerged in redistilled benzene in a 500 ml flask and shaken at 100 rpm for 24 hours on a mechanical shaker to remove the oil coating. This process was followed by straining the plant litter from the benzene-oil mixture using a 1 mm mesh screen. The T. latifolia litter was then reduced to approximately 5 mm length pieces, and both litter types were returned to the flask with fresh benzene and again shaken for 24 hours at 100 rpms. The plant litter was strained from the benzene and submerged into fresh benzene to remove any remaining oily film. Finally, the litter was oven dried at 80°C for 24 hours and reweighed to 0.1 mg. The final weight was the amount of plant litter remaining on that sampling date, and the weight difference before and after the oil extraction with benzene was the amount of oil on the litter. Preliminary analyses assured that the oil-extraction procedure did not change the weight (or other measured parameters) of the plant litter. Additionally, unoiled (control) litter was also subjected to the benzene treatment throughout the experiment without significant weight loss (Appendix E).

Plant litter from both lakes was analyzed for ash, phosphorus, and nitrogen content on each sampling date. Ash content was determined by ashing the litter at 550°C for at least 2 hours. Phosphorus content of the ash was determined using acid-persulfate digestion followed by the ascorbic-acid test for reactive phosphorus (APHA 1980). The percent nitrogen content of the litter was determined using a Coleman Model #29 Nitrogen Analyzer. Carbon content was calculated by assuming that the carbon was 47.5 percent of ash-free dry weight (Carpenter 1980).

Laboratory Experiment

Litter bags containing a known weight of oiled (with WC) or unoiled P. foliosus litter were prepared using the same technique as in the field portion of this study. Four of these litter bags were placed in separate laboratory aquaria containing natural sediment from either BL or NFL and a synthetic aqueous medium simulating the appropriate lake chemistry (Table 6). Duplicate experimental units were established for both oiled and unoiled litter and for each lake, making a total of eight experimental aquaria in all. Approximately equal plant mass to water volume and plant mass to sediment surface ratios were maintained throughout the experiment for all treatments. The aquaria were kept in the dark to preclude autotrophic production. Air was continuously bubbled through a diffuser to maintain oxygen in the water.

The average water residence time in all aquaria was 21 d. Concentrations of ammonia, nitrite, nitrate, orthophosphorus and total phosphorus in the aqueous medium were determined on days 0, 1, 3, 7, 14, 28, and 35 of the experiment for each aquarium. Ash, phosphorus, and nitrogen content of the plant litter and total sediment phosphorus were determined on days 0, 14, and 35. An attempt was made to quantify total phosphorus associated with oil on the litter bag material on day 35. Techniques for the nutrient analyses not already described appear in Appendix F. A mass balance technique was used to estimate the quantity of nutrients released or taken up by the decomposing litter between sampling intervals.

Data Analysis

The decomposition model developed by Godshalk (1977) (Equation 8, Figure 1) was used to describe the decay of litter in these experiments.

Data were fit to the model and parameters determined using the computer program appearing in Appendix G.

Temperature corrections (to 20°C) were made on field decomposition rate data using the temperature correction model presented by Schneiter and Grenney (1982). That model states,

$$K_T = K_R f' \quad . \quad . \quad . \quad . \quad (11)$$

where

- K_T is the decay coefficient at any temperature
- K_R is the decay coefficient at the reference temperature (i.e. 20°C)

$$f' = \frac{(1 + G_\ell (\exp[\gamma(T_R - T_\ell)] - 1)) \exp[\gamma(T - T_R)]}{1 + G_\ell [\exp(\gamma(T - T_\ell)) - 1]}$$

- T_R is a given reference temperature
- T_ℓ is the lower threshold temperature
- G is the upper threshold temperature
- T the temperature for which "f'" is required
- G_ℓ is the temperature correction coefficient at T_ℓ

$$\gamma = (T_\mu - T_\ell)^{-1} \ln \frac{0.98 (1 - G_\ell)}{G_\ell (1 - 0.98)}$$

Parameter values used were: upper threshold temperature (T_μ) is 37°C (Carpenter and Adams 1979), lower threshold temperature (T_ℓ) is 1.0°, and lower temperature adjustment factor (G_ℓ) is 0.11. The latter two values are within a range given by Grenney and Kraszewski (1981). A copy of the computer program used to correct for temperature with the above model is presented in Appendix H.

Decay coefficients for P. foliosus at five controlled temperatures (5, 9, 11, 20, and 22°C) were determined to calibrate the temperature correction model. The procedure to obtain the decay coefficients involved placing litter bags containing plant litter in dark aquaria which were maintained at the desired temperature in laboratory refrigerators or incubators. The duration of these experiments was 35 days and the aqueous medium residence time in the aquaria was approximately 20 days (maintained by fresh medium exchange every other day). The number of replicates at each temperature varied from 4 to 8.

A two by two factorial analysis of variance model was used to analyze the field data obtained for decomposing plant litter (the factors were treatment by oil and time).

RESULTS

Litter Decomposition Rates

The proportions of plant litter remaining throughout the year for all experimental treatments were fit to Equation 8 (Figure 1). Results are graphically presented in Figures 37 and 38. Regression estimates of model parameters with corresponding correlation coefficients (r^2) are presented in Table 26. High values of K_o indicate rapid initial decomposition of the plant litter (e.g. control *P. foliosus* litter). High values for the parameter "a" means that the rate of decomposition is quickly decreasing through time (e.g. oiled *Typha* litter in both lakes). An illustration of the fit of a typical set of data over a year's period to Equation 8 is presented in Appendix Figure G-1.

In both lakes oiled, *T. latifolia* litter initially lost mass at a greater rate than unoiled control litter (Figures 37 and 38). Following this initial stage, however, decomposition was more rapid for unoiled *T. latifolia*. Decomposition proceeded at a more rapid rate for unoiled *P. foliosus* litter than for oiled litter throughout the entire experiment. The differences were more pronounced in NFL than in BL for oiled versus unoiled *P. foliosus* litter.

Table 26. Paramer values and correlation coefficients based on Equation 8 for various lakes, litter types, and treatments.

	BEAR LAKE K_o	a	r^2
T. latifolia			
Control	0.0108	0.0094	0.95
S. La. Crude	0.0120	0.0144	0.95
Wyo. Crude	0.0180	0.0250	0.96
P. foliosus			
Control	0.0658	0.0154	0.99
S. La. Crude	0.0394	0.0185	0.85
Wyo. Cryde	0.0440	0.0155	0.97
	NEW FORK LAKE K_o	a	r^2
T. latifolia			
Control	0.00248	0.0027	0.97
S. La. Crude	0.00446	0.0125	0.97
Wyo. Crude	0.00869	0.0216	0.94
P. foliosus			
Control	0.0708	0.0204	0.99
S. La. Crude	0.0286	0.0257	0.76
Wyo. Crude	0.0360	0.0329	0.76

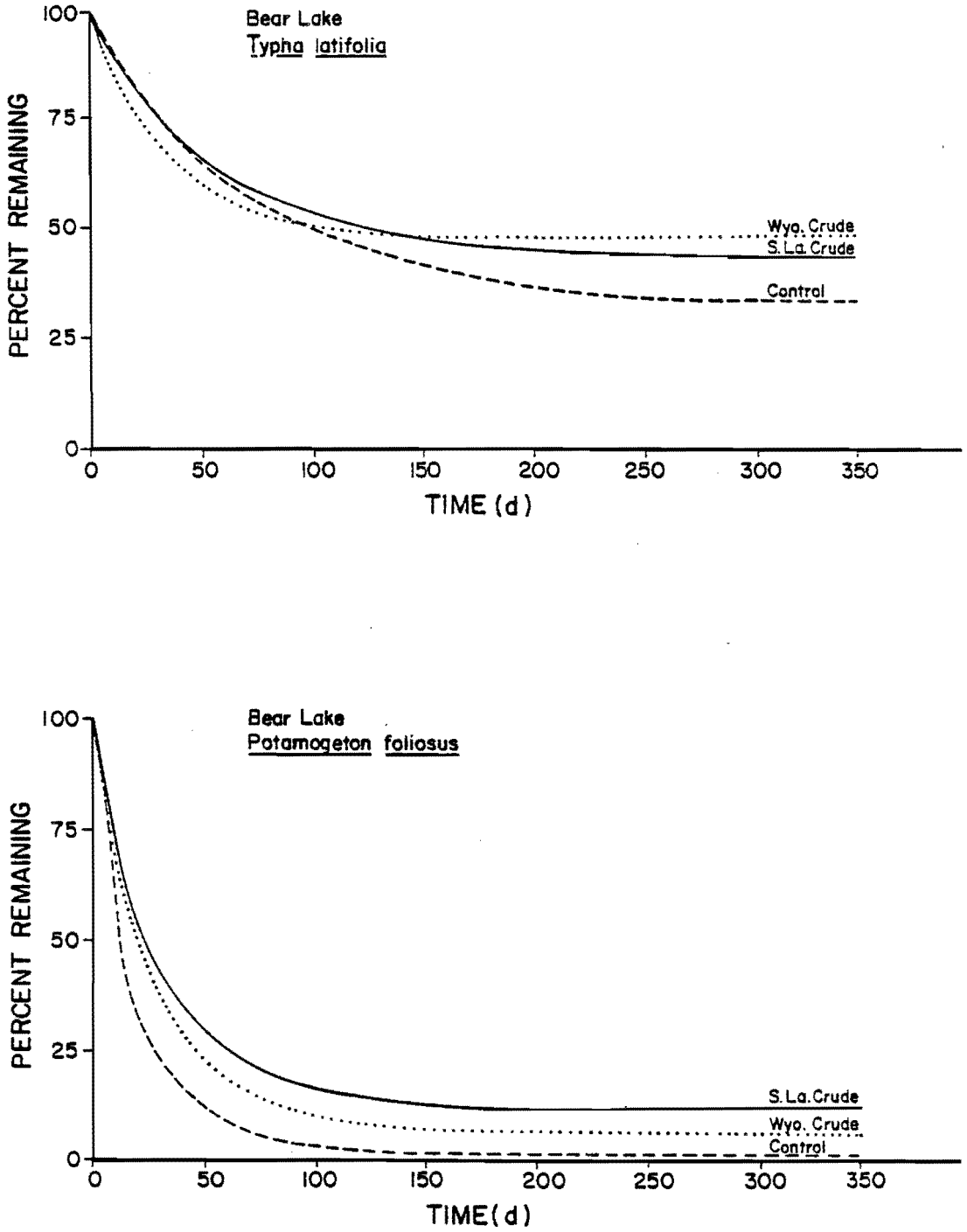


Figure 37. The percent of plant litter remaining through time as fit by Equation 8.

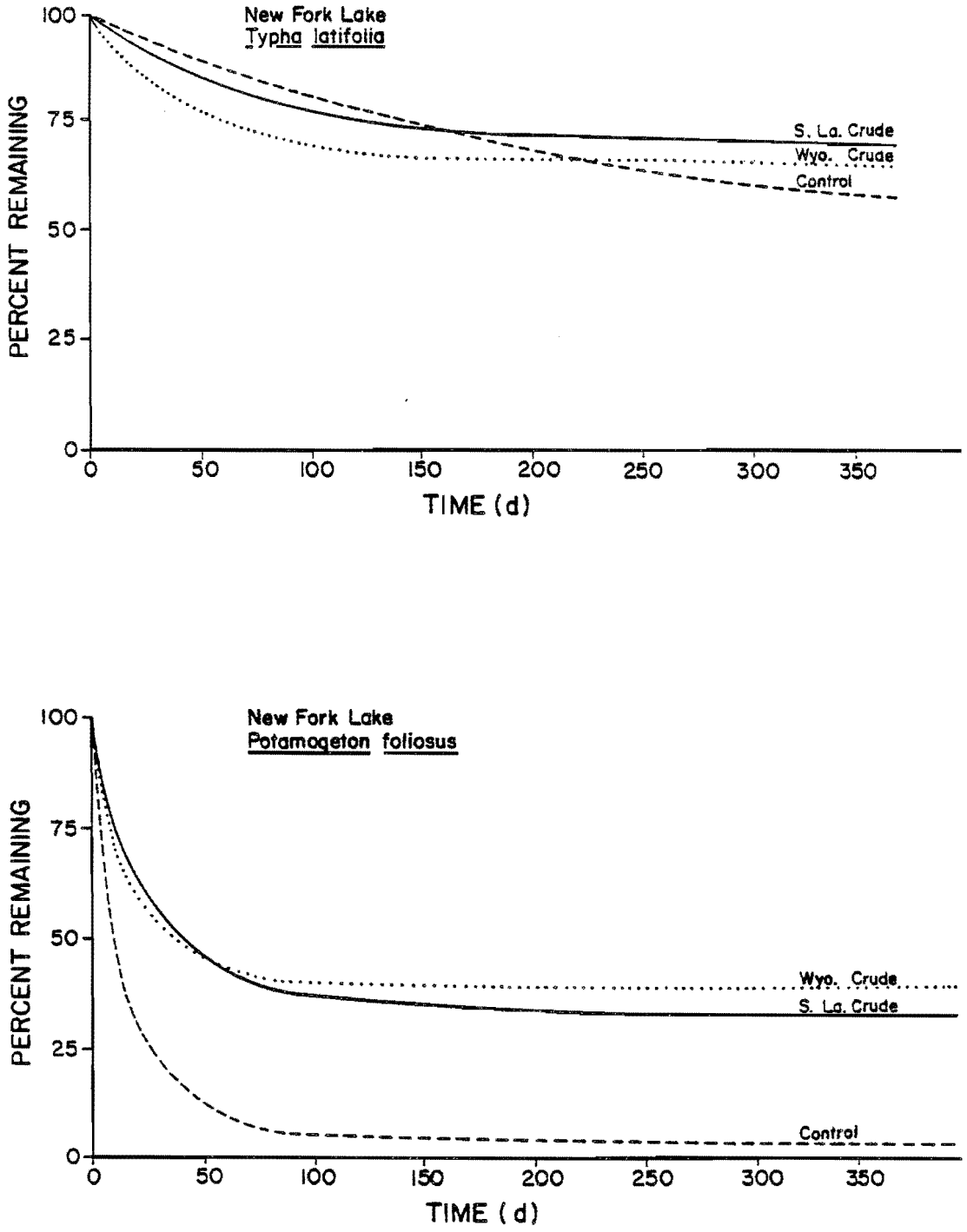


Figure 38. The percent of plant litter remaining through time as fit by Equation 8.

Results from an analysis of variance comparing treatment effects on the litter mass remaining for the nine sampling dates throughout a year are shown in Table 27 and Appendix I. The amount of litter remaining is significantly different between treatments for both plant species in both lakes. Individual treatment comparisons (based on least significant differences) are presented in the last three columns of Table 27. These results demonstrate that the average amount of litter remaining was greater for the oiled than for the control litter in both lakes for both plant species. Date and treatment-date interactions were also significant (except for Bear Lake P. foliosus). Significant date difference indicates the amount of plant material decreased significantly through time. Significant treatment-date interactions reflect a different pattern of weight loss throughout time for oiled versus unoiled litter. Treatment-date interactions are most apparent for T. latifolia in both lakes; initially, the oiled litter weight loss was more rapid than that of unoiled litter, but later in the year unoiled litter decomposed more rapidly (Figures 37 and 38). Individual treatment and control-treatment statistical comparisons are presented in Appendix I.

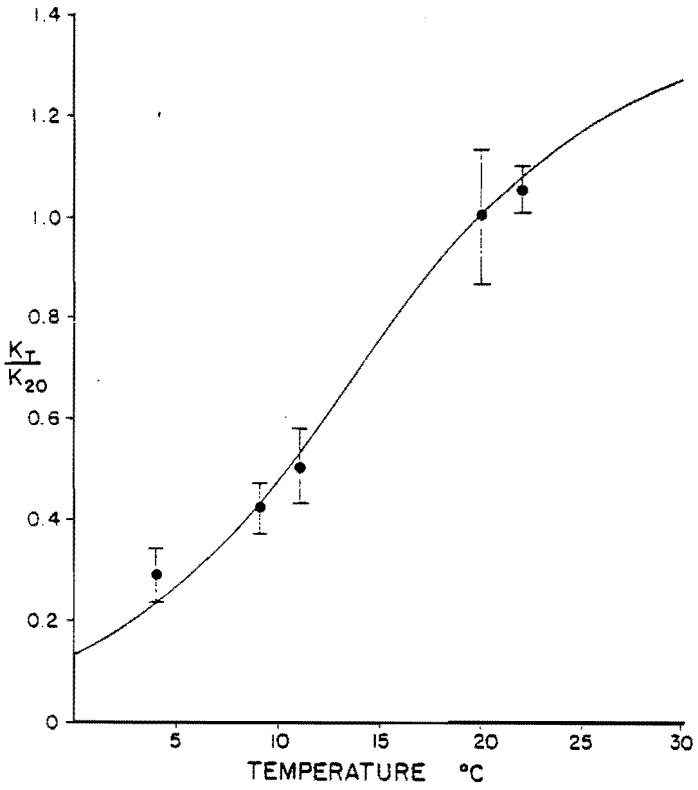


Figure 39. Temperature correction factors as a function of different temperatures. Mean laboratory data at various temperatures are represented by points and the standard deviation by brackets.

Temperature Corrected Decomposition Patterns

The curve of temperature correction factors for temperatures between 0 and 30°C is shown in Figure 39. Laboratory obtained mean values (4 to 8 replicates per temperature) illustrate agreement with the model prediction. The relationship was used to correct all lake decomposition rates to 20°C. This correcion permitted comparisons within a treatment (or control) to be made between BL and NFL (Figures 40-42).

Direct comparisons can be made between these lakes within a treatment for P. foliosus litter because of similar control litter decomposition rates (Figure 40). The same cannot be said for T. latifolia, which had higher decomposition rates for its control litter in BL than in NFL, when corrected to 20°C. Values for the decomposition model parameters, corrected to 20°C, are shown in Table 28. Oil apparently had a much greater effect on the decomposition of NFL P. foliosus litter than on that litter in BL. This is shown by the lower rate of decomposition and less complete loss of oil P. foliosus litter in NFL versus BL (Figures 41 and 42 and Table 28).

Oil Loss from Plant Litter

The pattern through time of oil loss from plant litter in the experi-

Table 27. Comparisons between plant litter remaining for oiled and unoiled litter on nine dates over a year's time.

Plant	Statistical Effect	Overall Significance	Average Percent Plant Litter Remaining		
			Unoiled	S. La. Crude	Wyo. Crude
		BEAR LAKE			
T. latifolia	Treatment	*[a]	63.9A[b]	67.6B	65.7AB
	Dates	**			
	Tmt. x Dates	**			
P. foliosus	Treatment	**	25.1A	37.1B	34.5B
	Dates	**			
	Tmt. x Dates	ns			
		NEW FORK LAKE			
T. latifolia	Treatment	**	81.8A	84.9B	79.4A
	Dates	**			
	Tmt. x Dates	**			
P. foliosus	Treatment	**	23.3A	50.6B	51.7B
	Dates	**			
	Tmt. x Dates	**			

Additional information on the statistical analysis can be found in Appendix I, Table I-2.

[a] Significant difference at $\alpha = 0.05$ (*), $\alpha = 0.01$ (**) or not significant (ns).

[b] Values in a given row followed by the same letter are not significantly different ($\alpha = 0.05$) as determined by least significant differences.

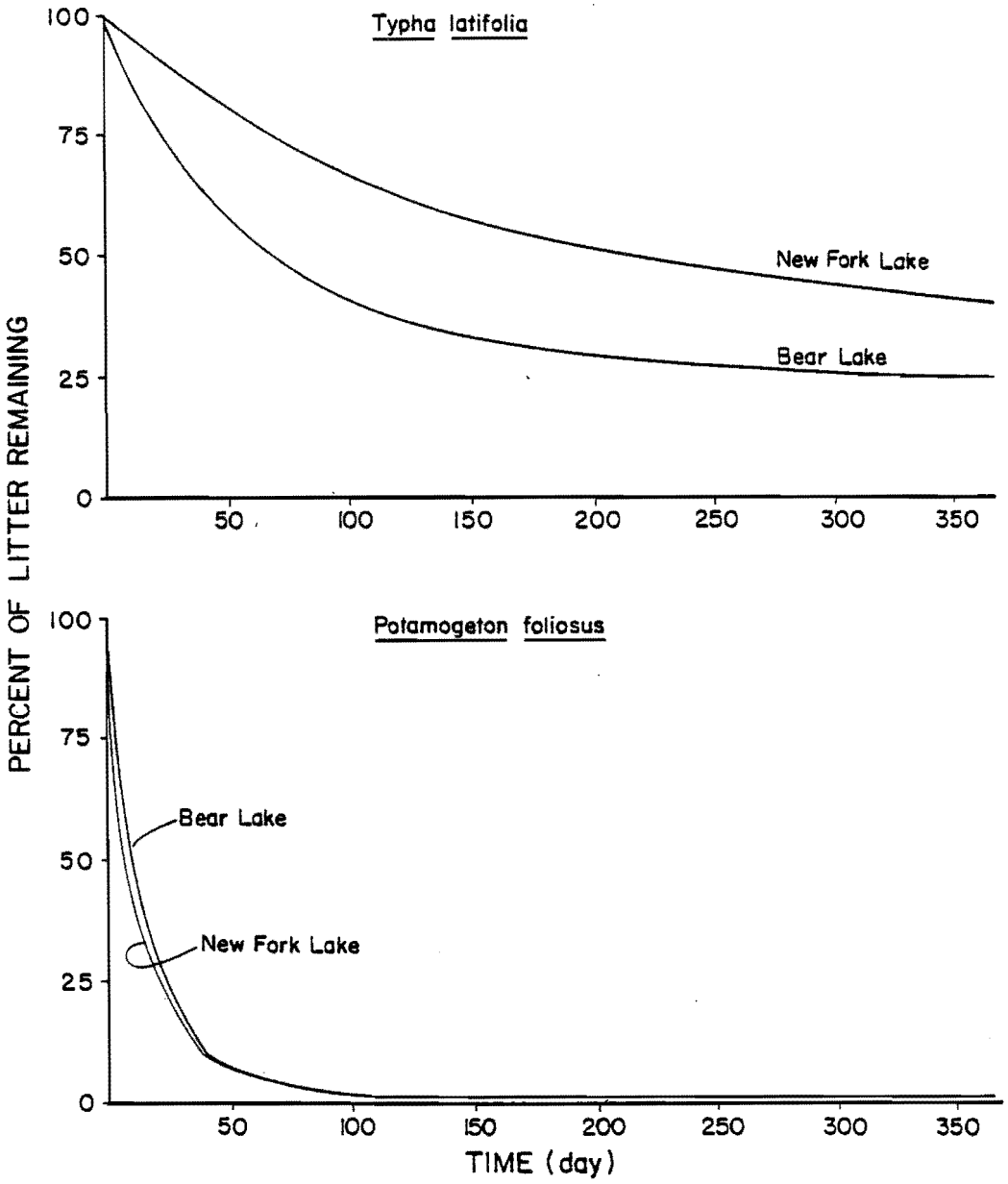


Figure 40. The percent of unoiled plant litter remaining through time in the two experimental lakes. Actual data were used to correct decomposition rates to 20°C and results were fit to Equation 8.

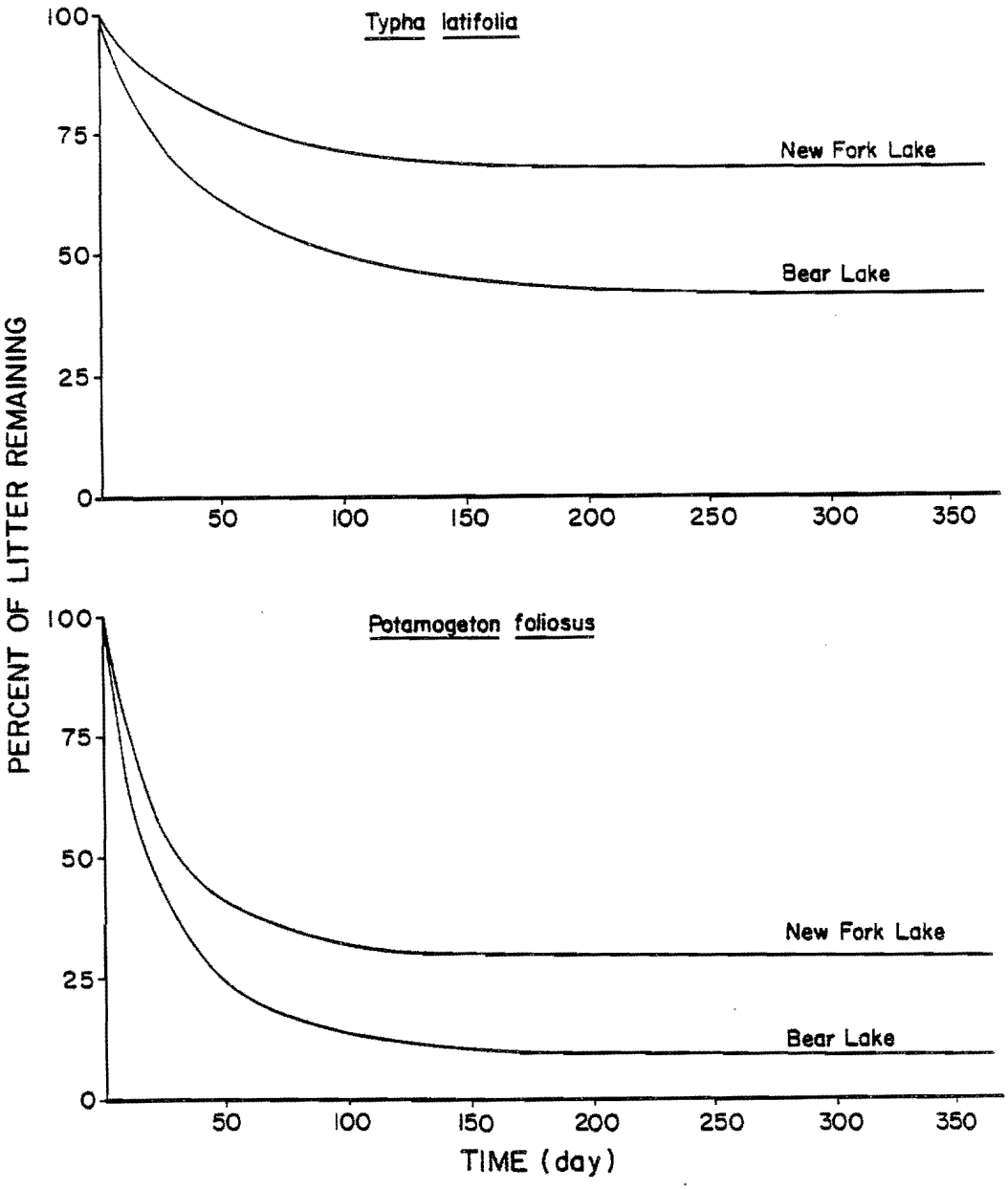


Figure 41. Percent of South Louisiana Crude oil litter remaining through time in the two experimental lakes. Actual data were corrected to 20°C and results were fit to Equation 8.

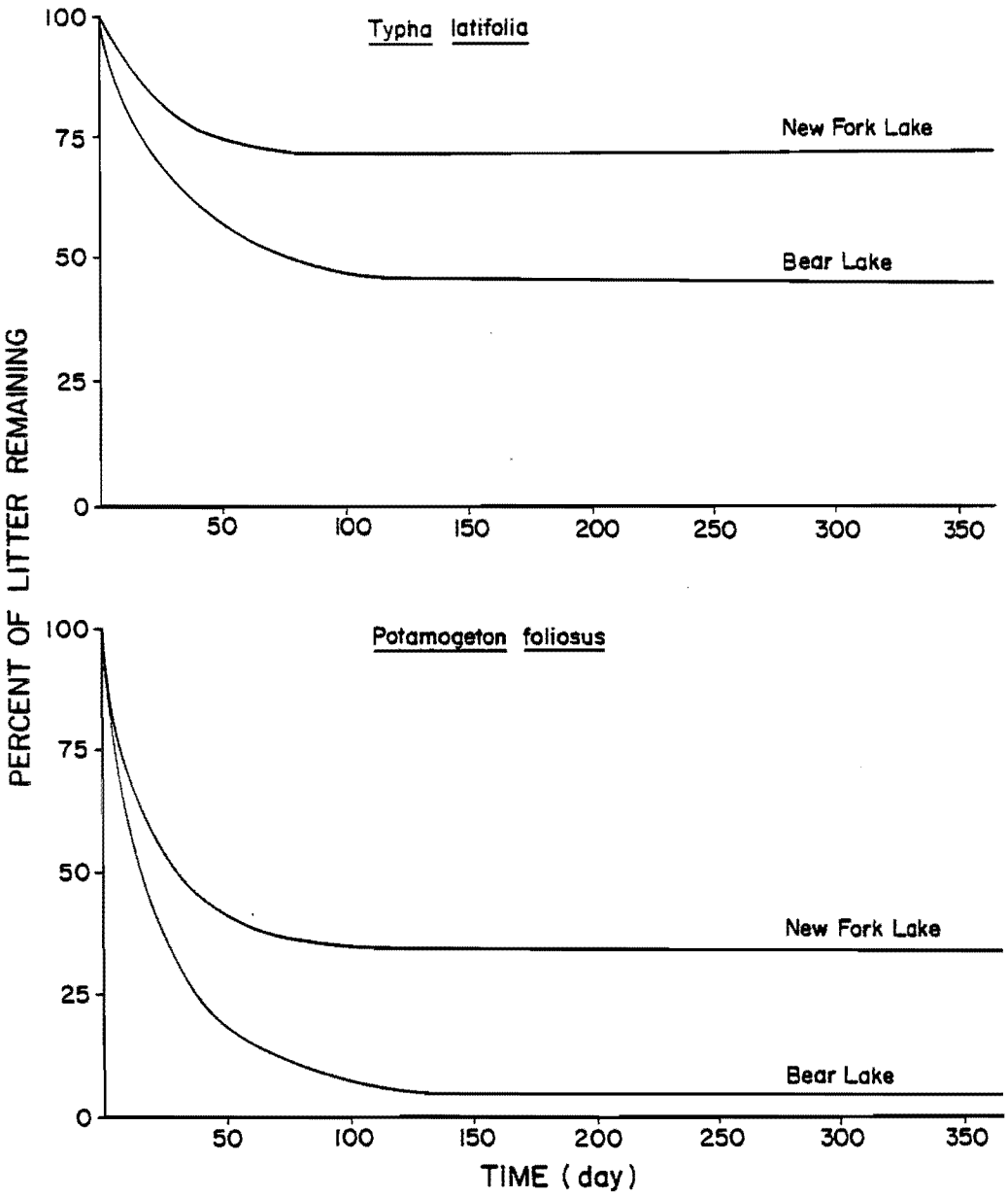


Figure 42. Percent of Wyoming Crude oil litter remaining through time in the two experimental lakes. Actual data were corrected to 20°C and results were fit to Equation 8.

Table 28. Parameter values for litter decomposition rates corrected to 20°C and fit to Equation 8 for various lakes, litter types, and treatments.

	BEAR LAKE	
	K_o	a
T. latifolia		
Control	0.0137	0.0094
SLC	0.0147	0.0168
WC	0.0192	0.0241
P. foliosus		
Control	0.0704	0.0140
SLC	0.0427	0.0179
WC	0.0472	0.0138
	NEW FORK LAKE	
	K_o	a
T. latifolia		
Control	0.0051	0.0045
SLC	0.0075	0.0193
WC	0.0157	0.0483
P. foliosus		
Control	0.0769	0.0160
SLC	0.0322	0.0266
WC	0.0381	0.0350

mental lakes is shown in Figures 43 and 44. All data are normalized to the amount of oil associated with the plant litter on day three of the experiment (i.e., oil rapidly lost by physical means before day 3 was not included). Table 29 contains results of a statistical analysis of the oil loss data.

Considering both plant species and both oil types, on the average more oil was lost from BL plant litter than from NFL plant litter. Also, *P. foliosus* litter lost more than did *T. latifolia*, considering both oil types and lakes. With all dates, both plant species and both lakes considered, more SLC was lost from plant litter than WC. Both oil types decreased in quantity through time for both plant species and lakes.

The information in Table 29 shows that *P. foliosus* litter lost a greater proportion of its oil than *T. latifolia* in BL. This was not true in NFL. Additionally, there was a greater proportion of oil loss from *P. foliosus* litter in BL than in NFL, but there was no difference in oil loss from *T. latifolia* between lakes. Analyzing other comparisons, a greater proportion of SLC than WC was lost in BL. In NFL the overall average proportion of loss was equal for the two crude oils. On the average, more of both crude oils was lost in BL than NFL. There was no plant species--oil type interaction; for example, the loss from *T. latifolia* was not unlike that from *P. foliosus* relevant to differences between SLC and WC.

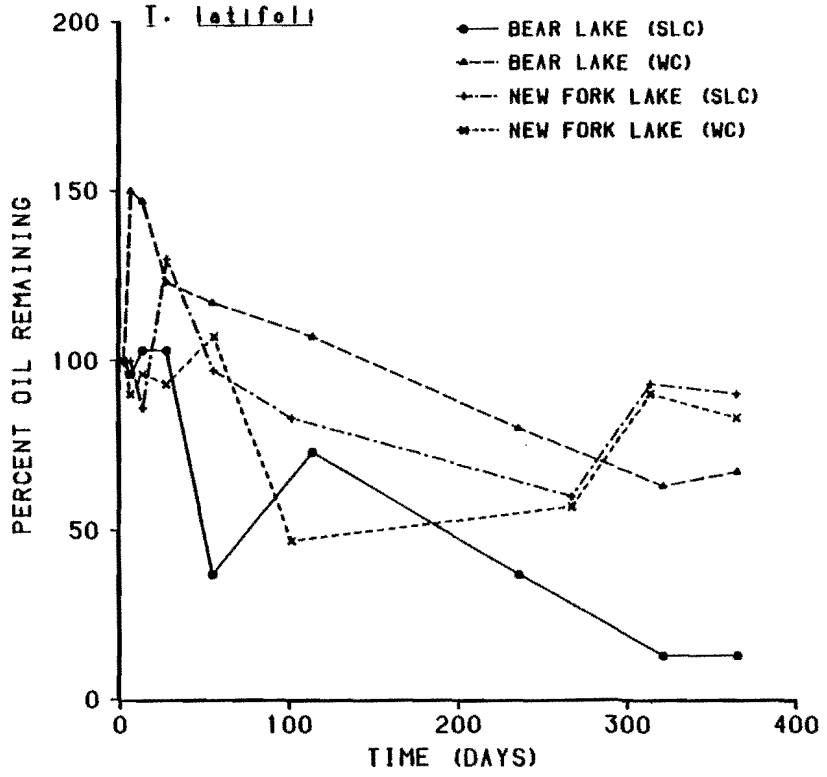


Figure 43. Oil loss from T. latifolia over a year's period.

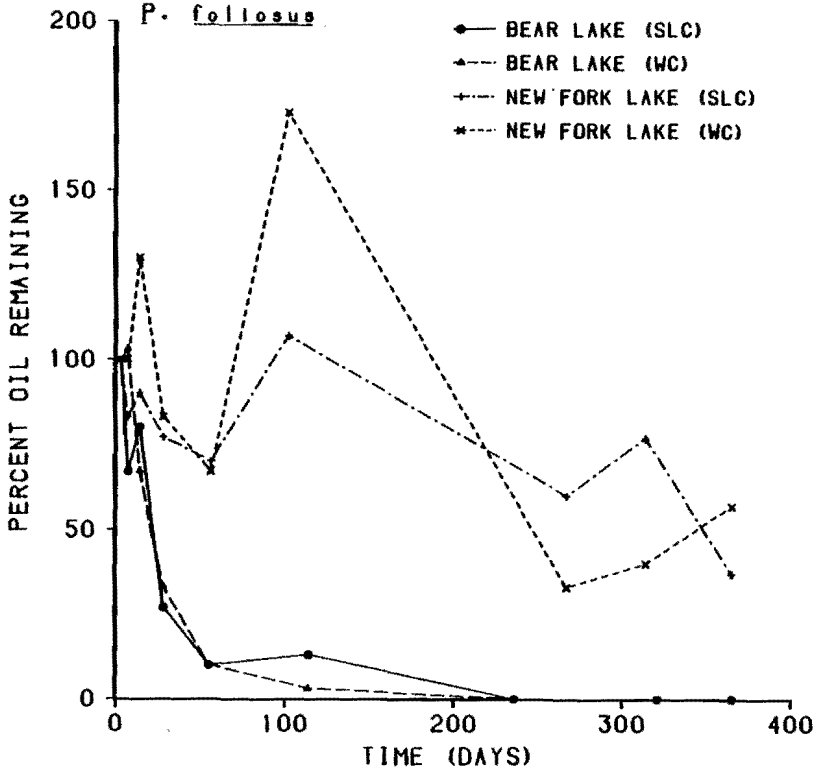


Figure 44. Oil loss from P. foliosus over a year's period.

Table 29. Summary information on the quantity of oil remaining on the plant litter throughout the year's experiment.

Comparison	Overall Significance Level	Comment	Significance Level of Specific Comparisons
Lakes	**[a]	Oil loss from plant litter in Bear Lake was more rapid than in New Fork Lake	
Species	**	Oil loss from P. foliosus litter was more rapid than T. latifolia	
Oil Type	**	S. La. Crude was lost from plants more rapidly than Wyo. Crude	
Dates	**	The oil coating on plant litter decreased in quantity through time	
Lakes--Species	**	Oil loss from P. foliosus more rapid than from T. latifolia in Bear Lake	**
		Oil loss from P. foliosus more rapid in Bear Lake than New Fork Lake	**
		T. latifolia versus P. foliosus in New Fork Lake	ns
		T. latifolia in Bear Lake versus New Fork Lake	ns
Lake--Oil Type	**	S. La. Crude loss more rapid than Wyo. Crude in Bear Lake	**
		S. La. Crude loss more rapid in Bear Lake than New Fork Lake	**
		Wyo. Crude loss more rapid in Bear Lake than New Fork Lake	**
		S. La. Crude versus Wyo. Crude in New Fork Lake	ns
Species--Oil Type	ns		
Lake--Dates	**	Oil decreased more rapidly in Bear Lake than New Fork Lake through time	
Species--Dates	*	Oil on P. foliosus decreased more rapidly than it did on T. latifolia	
Oil--Dates	ns		

Additional information on the statistical analysis can be found in Appendix I, Table I-3.
[a]Significant difference at $\alpha = 0.05$ (*), $\alpha = 0.01$ (**), or not significant (ns).

Plant litter in BL lost oil faster than did litter in NFL. Also, over both lakes and oil types, P. foliosus lost oil at a more rapid rate than did T. latifolia.

Invertebrates Associated with Plant Litter

The numbers and types of invertebrates associated with oiled and unoiled decomposing plant litter on the final day of the experiment are shown in Table 30. Unoiled litter had more invertebrates than did oiled litter in both lakes. Although these data were quantified only on day 365 of the experiment, visual observations indicated the difference was greater earlier in the experiment before the oil weathered.

Dissolved Oxygen Utilization Rates

Dissolved oxygen utilization rates for the decomposer community associated with plant litter of various treatments are shown in Figures 45 and 46. The major purpose for this presentation is to demonstrate effects of the crude oil on oxygen consumption by comparing treatments and controls date by date. Results of statistical analysis of variance tests are presented to help interpret these data (Table 31 and Appendix I).

There were no significant differences in the yearly average oxygen consumption rates between controls and treatments in BL. Significant differ-

Table 30. Number of invertebrates associated with decomposing T. latifolia litter on day 365 of the decomposition experiment.

Lake	Invertebrate	Control	SLC	WC
Bear Lake	CHIRONOMIDAE (True midges)	24.0 (2.5)	3.3 (2.1)	0.7 (1.2)
	HIRUDINEA (Leeches)	0.3 (0.6)	0	0
New Fork Lake	CHIRONOMIDAE (True midges)	22.3 (17.6)	0	1.1 (1.2)
	Paraleptophlebia sp. (May flies)	9.0 (13.9)	0	0
	Hyallella azteca (Amphipods)	0	0	2.7 (4.6)
	PELECYPODA (Fingernail clams)	0	0	1.0 (1.7)
	PLECOPTERA (Stone flies)	0.3 (0.6)	0	0

Mean numbers (n=3) with standard deviations are in parentheses.

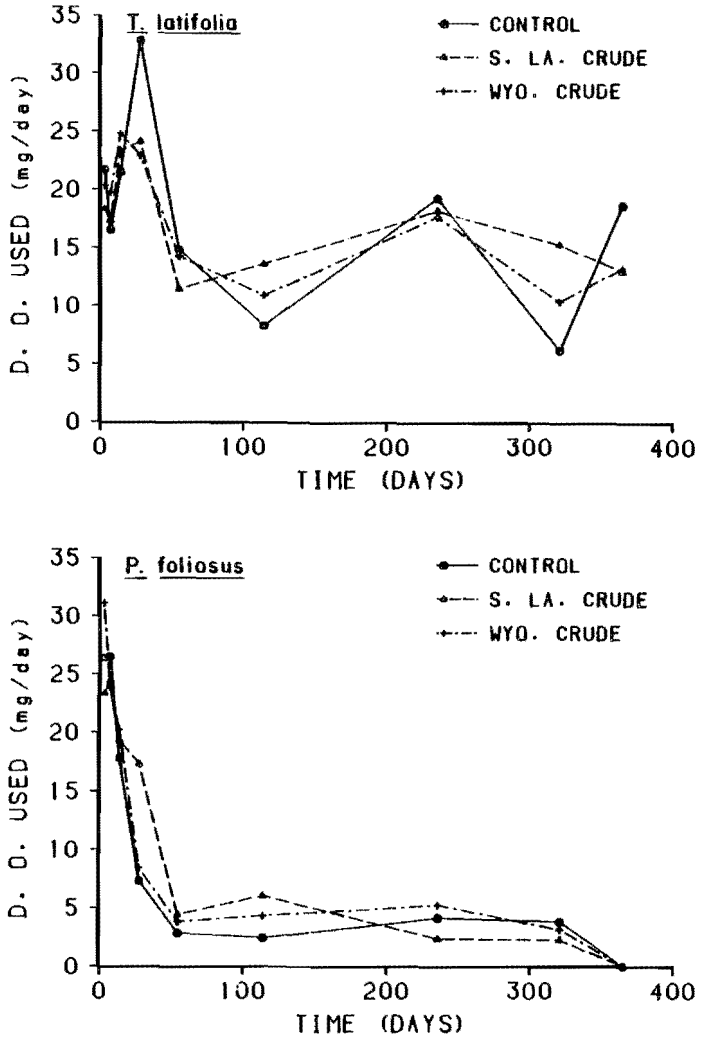


Figure 45. Rate of oxygen utilization of decomposer communities on plant litter in Bear Lake.

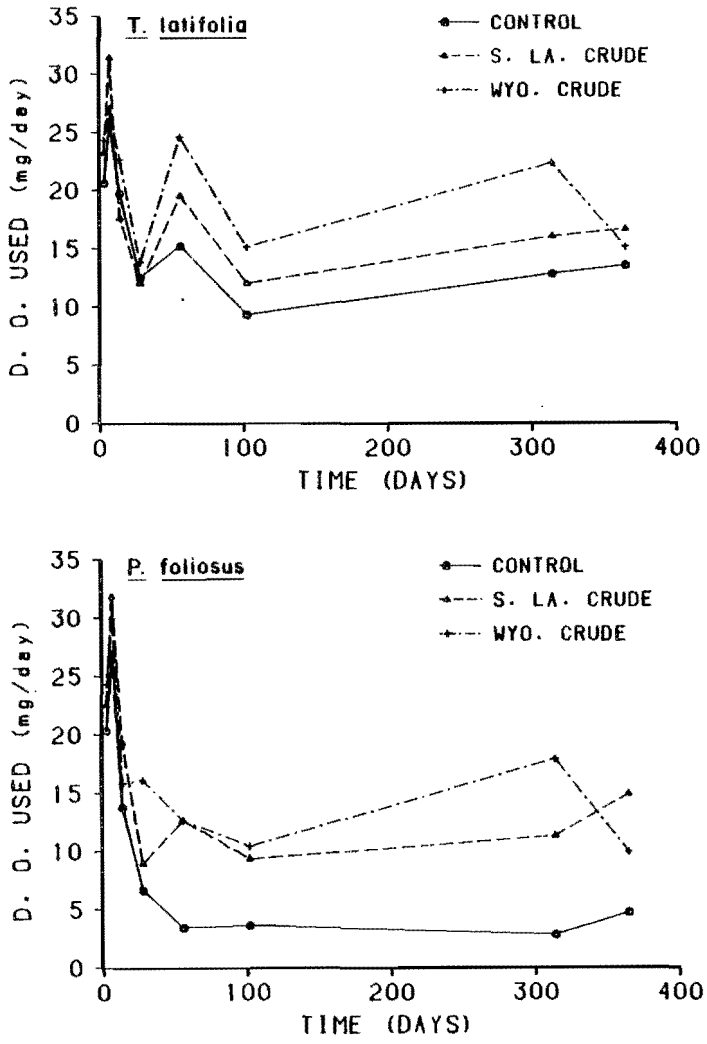


Figure 46. Rate of oxygen utilization of decomposer communities on plant litter in New Fork Lake.

Table 31. Comparisons between the overall average oxygen utilization rate for oiled and unoiled plant litter.

Plant	Statistical Comparison	Overall Significance	Average Oxygen Utilization Rates (mg DO consumed/g initial litter wt-d)		
			Unoiled	S. La. Crude	Wyo. Crude
		BEAR LAKE			
T. latifolia	Treatment	ns[a]	3.13[A][b]	3.03[A]	3.01[A]
	Dates	**			
	Tmt. x Dates	**			
P. foliosus	Treatment	ns	4.82[A]	5.12[A]	5.04[A]
	Dates	**			
	Tmt. x Dates	**			
		NEW FORK LAKE			
T. latifolia	Treatment	**	2.67[A]	3.07[B]	3.39[C]
	Dates	**			
	Tmt. x Dates	ns			
P. foliosus	Treatment	**	4.45[A]	6.66[B]	6.86[B]
	Dates	**			
	Tmt. x Dates	*			

[a]Significant difference at $\alpha = 0.05$ (*), $\alpha = 0.01$ (**) or not significant (ns).

[b]Values in a given row followed by the same letter were not significantly different at the 5 percent level as determined by LSD.

ences did exist between dates for both plant species in BL; the difference was largely due to decreasing respiration rates as the experiment progressed. Treatment-date interaction comparisons were also significant in BL for both plant species.

A significant overall treatment effect existed in NFL for both plant species. The oil treatments caused higher average oxygen consumption rates than that of control litter, additionally WC treated T. latifolia litter had higher respiration rates than SLC treated litter. Overall date effects were significant for both plant species and treatment-date interactions in NFL for P. foliosus.

The oil had no apparent initial inhibitory effects on the rate of decomposer activity, as measured by dissolved oxygen consumption. Of all comparisons over the first 14 days in both lakes for treatments within a plant species, only three are significantly different. Two of these differences resulted because oiled litter was consuming dissolved oxygen at a greater rate than unoiled litter. The two oil treatments had different utilization rates for the third difference (Appendix I). In general, respiration rates for oiled litter were higher than for unoiled litter through the initial 14 days, even when the difference was not statistically significant.

For the remainder of the experiment (351 d), oiled litter for both plant species in NFL had higher respiration rates than did unoiled litter. At least one of the oiled treatments was significantly higher than the unoiled control on three of the remaining six dates for T. latifolia and on all six dates for P. foliosus. Except at the end of the experiment (day 365), WC caused higher respiration rates than did SLC for both plant species in NFL (this consistent difference was statistically significant on days 3 and 28 for P. foliosus and day 3 for T. latifolia).

Patterns concerning effects of crude oil on respiration rates were not clear in BL after day 14; unoiled T. latifolia litter had higher respiration rates associated with it than oiled litter on day 28 (WC and SLC) and day 365 (SLC). However, the control litter had a significantly lower rate than SLC treated litter on day 321. Overall, the yearly oxygen consumption pattern for T. latifolia in BL was inconsistent; on alternate dates respiration rates were first higher then lower for oiled treatments relative to control litter. Differences between oil types were also inconsistent.

A clear pattern for respiration rates between oiled and unoiled P. foliosus was also absent in BL. As with T. latifolia, respiration rates were sometimes higher for controls, and sometimes higher for oiled treatments on a date to date basis. Only one significant difference occurred after day 14; on day 28 the WC treatment had a higher respiration rate than either the SLC or the control litter.

Oxygen consumed per plant mass decomposed

Values of the total mass of oxygen consumed over the duration of the experiment divided by the total mass of litter decomposed (in the same units) for the various plants and treatments in both experimental lakes are presented in Table 32. Results of tests for significant differences caused by the oil are presented in Table 33. A significantly larger mass of oxygen was utilized per oiled litter decomposed in all cases except P. foliosus in Bear Lake. Significant differences in the oxygen consumed per plant mass decomposed ratio do not exist in either lake between the two oiled treatments (i.e. SLC vs WC). Results of the tests for significant differences between lakes are presented in Table 34. NFL's value is higher than BL's in all cases where significant differences were found.

Table 32. Ratio of oxygen mass utilized to mass of plant litter lost over a year's period.

Lake	Plant	Treatment	Mean	S_d
			(g Oxygen Utilized/g Litter Lost)	
Bear	T. latifolia	Control	1.36	0.03
		S. La. Crude	1.70	0.18
		Wyo. Crude	1.65	0.09
	P. foliosus	Control	0.73	0.09
		S. La. Crude	0.88	0.24
		Wyo. Crude	0.89	0.12
New Fork	T. latifolia	Control	1.63	0.20
		S. La. Crude	2.92	0.56
		Wyo. Crude	3.09	0.80
	P. foliosus	Control	0.73	0.20
		S. La. Crude	2.46	0.22
		Wyo. Crude	3.48	0.94

Table 33. Results of tests for significant differences between oiled and unoiled litter for the mass of oxygen utilized per mass of plant litter decomposed over a year's period (i.e., those values listed in Table 31).

		Statistical Comparisons		
Lake	Plant	Control vs S. La. Crude	Control vs Wyo. Crude	S. La. Crude vs Wyo. Crude
Bear	T. latifolia	**[a](C<SLC)	**(C<WC)	ns
	P. foliosus	ns	ns	ns
New Fork	T. latifolia	**(C<SLC)	**(C<WC)	ns
	P. foliosus	**(C<SLC)	**(C<WC)	ns

[a]Significant difference at $\alpha = 0.01$ (**) or not significant (ns).

Table 34. Results of tests for significant differences between lakes in the mass of oxygen utilized per mass of plant litter decomposed over a year (i.e., those values listed in Table 31).

Statistical Comparison	T. latifolia	P. foliosus
Controls	*[a](NFL > BL)	ns
S. La. Crude	**(NFL > BL)	**(NFL > BL)
Wyo. Crude	**(NFL > BL)	**(NFL > BL)

[a]Significant difference at $\alpha = 0.05$ (*), $\alpha = 0.01$ (**), or not significant (ns).

Litter Environment Nutrient Exchange

Nutrient loss from decomposing litter

Cumulative losses of nitrogen and phosphorus from decomposing P. foliosus are presented in Figures 47 and 48. These nutrient losses are expressed in mg lost per gram of litter at the onset of the experiment; therefore, the quantity reported lost is a function of the amount of litter decomposed. Figure 47 shows that nitrogen was lost more rapidly from unoiled plant litter than from the corresponding oiled litter. In situ unoiled litter approached 40 mg N lost per gram of initial plant litter by day 55 of the experiment in both lakes. Unoiled litter in the laboratory study approached 30 mg N lost per gram during the first 35 days of the experiment. Oiled plant litter lost from 7 to 43 percent less nitrogen than their unoiled counterparts.

The amounts of phosphorus lost by oiled and unoiled P. foliosus litter in BL and NFL and their associated simulated laboratory systems are shown in Figure 48. Phosphorus loss from unoiled plants was greater than from oiled litter within all sets of corresponding pairs (except in BL). Between 3 and 4 mg of phosphorus per gram initial litter was lost from the unoiled litter by day 55 in both natural lakes and by day 35 in the laboratory systems. The negative slope between days 28 and 55 in the lakes indicates phosphorus was being taken up by the litter decomposers from the surrounding water.

First order decomposition coefficients for the litter involved in this portion of the study are given in Table 35. The coefficients pertain only to the duration of the nutrient experiments (55 days for the lakes and 35 days for the laboratory systems). The laboratory decay coefficients for oiled litter is very similar between simulated lakes, but the actual lake values are quite different.

Carbon to nitrogen (C:N) and carbon to phosphorus ratios (C:P) were calculated for in situ P. foliosus litter throughout the year. Appendix J contains C:N and C:P ratios for all dates, treatments, both lakes and plant species. Figure 49 is a typical set of C:N results comparing oiled versus unoiled litter. Table 36 is a summary of statistical results comparing oiled

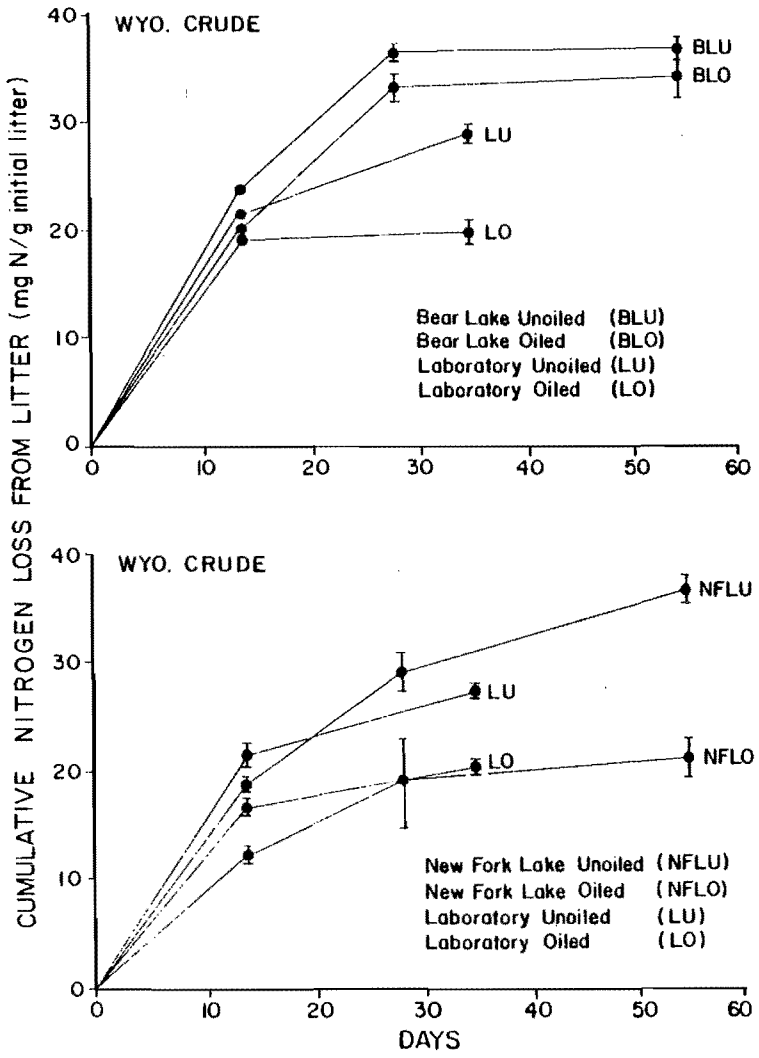


Figure 47. Cumulative nitrogen loss from plant litter through time.

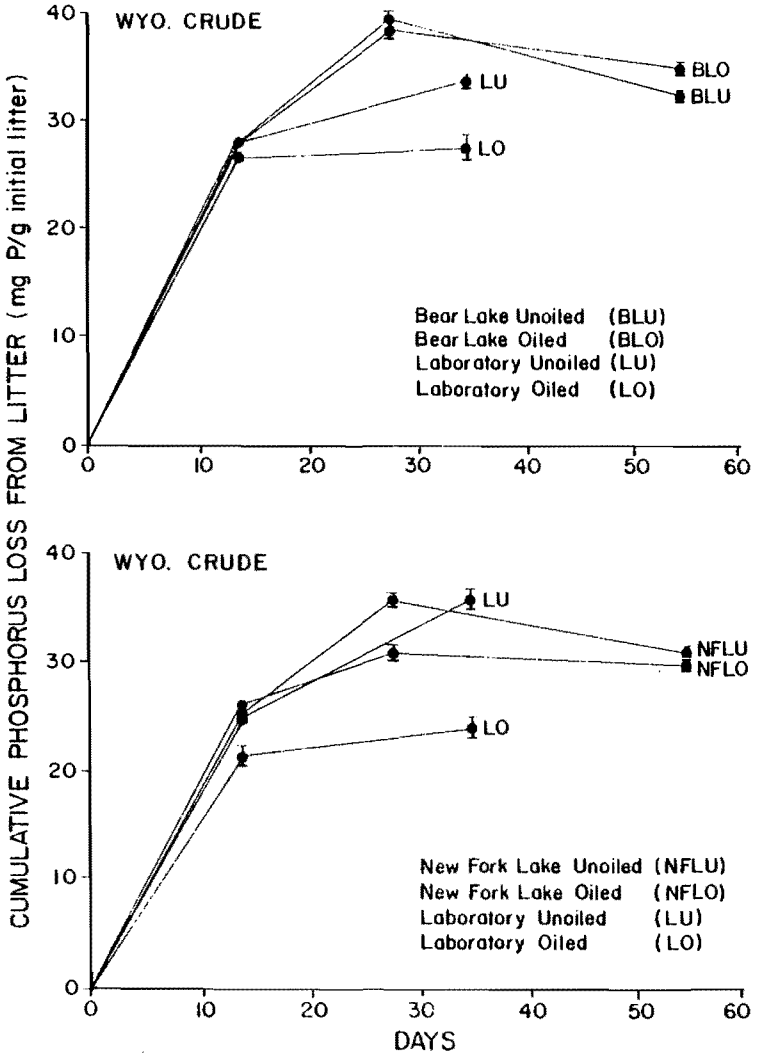


Figure 48. Cumulative phosphorus loss from plant litter through time.

Table 35. First order decay coefficients (K) for oiled and unoiled P. foliosus litter in two lakes and their simulated laboratory systems.

	Unoiled	Oiled
	K (day^{-1})	
Bear Lake	0.044	0.030
New Fork Lake	0.051	0.013
Simulated Bear Lake Experiment	0.033	0.017
Simulated New Fork Lake Experiment	0.028	0.016

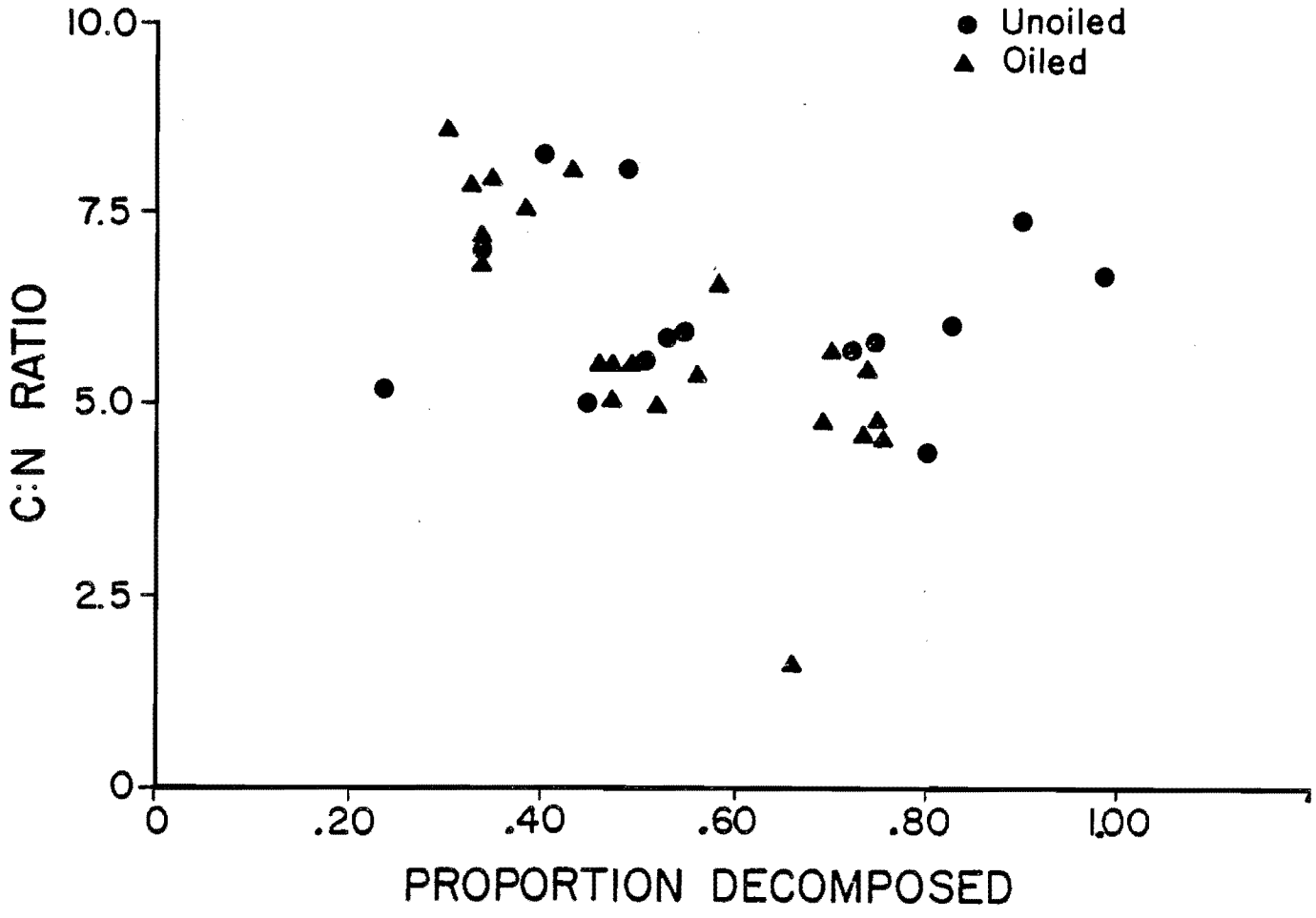


Figure 49. C:N ratio versus the proportion of litter remaining for oiled and unoiled P. foliosus litter in New Fork Lake (results are typical of C:N and C:P ratios of other plant-like categories).

and unoiled litter using analysis of covariance. No significant differences existed.

Nutrient mass balance in laboratory systems

The above analyses are based on the weight of nutrients lost per gram of initial litter weight. In Table 37 data are presented in terms of the weight of nutrients released to the surrounding waters per gram of litter decomposed over 35 days in the laboratory systems. The actual quantity of inorganic nutrients released to the water due to the decomposing litter (rather than the quantity lost from the plant litter) was

Table 36. Statistic summary of a C:N and C:P comparison between oiled and unoiled litter.

		F Ratio	Probability That Treatments Are The Same
C:N	Bear Lake	0.00008	0.993 (ns)[a]
	New Fork Lake	1.64	0.202 (ns)
C:P	Bear Lake	0.102	0.750 (ns)
	New Fork Lake	0.646	0.423 (ns)

[a]Not significantly different (ns), values of 0.05 would be considered significant.

Table 37. Quantities of nutrient released to surrounding water from unoiled and oiled *P. foliosus* litter over 35 days of decomposition.

Nutrient	Bear Lake Lab. System			New Fork Lake Lab..System		
	Unoiled	Oiled		Unoiled	Oiled	
	(mg Nutrient Released/g Litter Decomposed)					
Orthophosphate	4.65	3.01	*[a]	3.20	0.80	*
Total Phosphorus	5.31	3.60	*	3.76	1.47	*
Ammonia	2.04	0.03	*	2.34	0.39	*
Nitrite	2.01	0.03	**	0.52	0.07	ns
Nitrate	5.26	-0.54	*	6.25	-0.73	*
Total Inorganic Nitrogen	9.31	-0.47	**	9.10	-0.26	**

A negative value indicates the nutrient was removed from surrounding water.

[a]Significant difference at $\alpha = 0.05$ (*), $\alpha = 0.01$ (**) or not significantly different (ns).

Table 38. The percentage of nutrient loss recovered in the aqueous media for unoiled and oiled litter in Bear Lake and New Fork Lake laboratory systems.

Simulated Lake	Nutrient	Treatment	Nutrient Mass Released from Litter (mg/g litter decomposed)	Nutrient Mass Recovered in Water (mg/g litter decomposed)	Percent Recovered	Statistical Comparison
Bear	Inorganic phosphorus	Unoiled	5.08	4.65	91	
		Oiled	5.25	3.01	57	*a
	Inorganic nitrogen	Unoiled	44.5	9.31	21	
		Oiled	46.5	-0.47	0	**
New Fork	Inorganic phosphorus	Unoiled	4.69	3.20	69	
		Oiled	4.80	0.80	17	*
	Inorganic nitrogen	Unoiled	44.0	9.10	21	
		Oiled	45.4	-0.26	0	**

[a]Significant difference at $\alpha = 0.05$ (*) or $\alpha = 0.01$ (**).

used in these calculations. Additionally, the calculation was normalized per unit mass of plant litter decomposed rather than on per unit mass of initial plant mass. Results of this calculation will be referred to as nutrient release rates from decomposing litter. All nutrient release rates from oiled litter were found to be significantly lower than those from unoiled litter in both the BL and NFL laboratory systems (Table 37), with the exception of nitrite in the NFL system. A net loss of nitrogen from the surrounding water throughout the 35-day experiment was indicated by negative values of total nitrogen (Table 37) for the oiled treatments of both systems.

Percentages of total inorganic phosphorus and nitrogen lost from the litter and recovered in the aqueous phase of the laboratory systems are shown in Table 38. Significant differences between oiled and unoiled treatments, in the percent of nutrients recovered in the aqueous phase, exist for both nutrients in both laboratory lake systems. For each of the four comparisons (Table 38) a higher percentage of the nutrients lost by the unoiled litter was recovered in the ambient water than was recovered in the ambient water surrounding the oiled litter.

Sediment phosphorus concentrations (mg P per g sediment) for both laboratory systems are shown in Table 39. Statistically significant differences do not exist between control and treatment for any date, nor between dates for either treatment. Mean quantities of total phosphorus associated with the oil removed from a square cm of litter bag screening material on the final day of the laboratory experiments are also given in Table 39. The phosphorus analysis may have had some interference from the oil (a clouded condition appeared in laboratory flasks), but distinct and intense coloration indicated that phosphorus was present.

Table 39. Sediment and litter bag screening material phosphorus levels for both laboratory systems.[a]

Day	Bear Lake Laboratory Sediments (mg P/g Dry Sediment) Unoiled	Bear Lake Laboratory Sediments (mg P/g Dry Sediment) Oiled	Bear Lake Litter Bag Screen ($mg\ P/cm^2$ Screen)
0	34.8	34.8	
14	35.2	35.7	
35	34.7	34.2	0.175
	New Fork Lake Laboratory Sediments (mg P/g Dry Sediment) Unoiled	**New Fork Lake Laboratory Sediments (mg P/g Dry Sediment) Oiled**	**New Fork Lake Litter Bag Screen ($mg\ P/cm^2$ Screen)**
0	32.5	32.5	
14	32.5	31.9	
35	33.4	34.2	0.373

[a]Statistically significant difference ($\alpha = 0.05$) does not exist between treatments on a given date nor between dates within a treatment for either lake.

DISCUSSION

Litter decomposition was slowed by oil addition for both plant types in both lakes based on yearly average results of weight remaining. However, the activity of decomposer communities (as measured by dissolved oxygen consumption) on the oiled litter was either greater than (NFL) or equal to (BL) activity on the unoiled litter. Increased microbial activity and/or growth due to oil pollution in aquatic systems have often been reported in the literature (e.g. Colwell et al. 1978; Atlas et al. 1978; Walker et al. 1975; Lock et al. 1981a, b). Although this study supports those findings, they also suggest that important ecosystem functions may be altered by crude oil impacts. Specifically, the rate and extent of litter decomposition, oxygen utilization rates, and nutrient exchange between the litter and its surrounding water were shown to be affected by crude oil. Thus, spilled crude oil could have major impacts on freshwater ecosystems since the decomposition of autochthonous aquatic plants can regulate an entire lake's metabolism (Howard-Williams and Lenton 1975; Howard-Williams and Davies 1979; Carpenter 1980, 1981). Potential impacts of crude oil relevant to aquatic plant decomposition will be discussed in this section.

Patterns of Litter Decomposition

Decompositional trends over a period of 1 year for unoiled versus oiled litter were quite different between T. latifolia and P. foliosus litter (Figures 37-38). The two plant types have different chemical compositions (Boyd 1968; Boyd and Hess 1970) due mainly to their different growth forms. Emergent aquatic plants, such as T. latifolia, have a higher density of relatively refractory structural compounds than do submergent plants, such as P. foliosus. Submergent plants have no need for a high density of structural compounds because their weight is largely supported by the water (Godshalk 1977; Godshalk and Wetzel 1978a; Howard-Williams and Davies 1979). As previously noted, oil increased the early decompositional rate of T. latifolia. Increased rates of decomposition can occur when a substrate which is somehow deficient to microorganisms is added to a second substrate which remedies the deficiency (Gaudy and Gaudy 1980). Crude oil added to T. latifolia litter may have supplied a readily available carbon source which accelerated the initial decomposition rate of the litter. If this was the case, cooxidation of the oiled litter overshadowed toxic effects of the crude oils because T. latifolia is quite refractory due to its structural compounds (cellulose and lignin). Conversely, degradation of P. foliosus, which is easily biodegradable, was not stimulated by oil but oil inhibited its decomposition from the beginning.

An alternate explanation for the rapid initial decomposition of oiled T. latifolia is that crude oil physically changed the litter structure, making it more susceptible to abiotic leaching. However, leaching is a mechanism of rapid weight loss (Howard-Williams and Howard-Williams 1978; Godshalk and Wetzel 1978b), and greater weight loss for oiled T. latifolia (relative to control litter) lasted for 50 days in Bear Lake and 100 days in New Fork Lake. Therefore, increased leaching from litter resulting from structural changes by the oil does not appear to be the controlling mechanism for the acceler-

ated rate of oiled T. latifolia weight loss.

Oiled litter of both plant species in both lakes had a more rapidly decreasing rate of decomposition through time than their unoiled counterparts. This can be seen most clearly by comparing the parameter "a" of the decomposition model (Table 26) for unoiled and oiled litter within a lake-plant category. In all cases the value of this parameter, which defines the rate at which the initial decomposition rate is reduced through time, is greater for oiled than unoiled litter. As discussed later, the rapid reduction of decomposition rates of the oiled litter likely resulted from nutrient (particularly nitrogen) limitation to the decomposer organisms.

Interlake comparisons

Unoiled P. foliosus litter had very similar decomposition rates in BL and NFL (Figures 37, 38, and Table 26). However, the rate and extent of oiled P. foliosus litter decomposition was much greater in BL than in NFL (Figures 37 and 38 and Table 26). There are a number of potential explanations for the different impact that crude oils had on P. foliosus litter decomposition in the two lakes. First, the lakes had very different water types, but water chemistry differences did not cause substantial difference in decomposition rates of oiled litter in a laboratory experiment (see Table 35). Therefore, it is not likely that water chemistry caused the magnitude of interlake difference in the in situ experiment. Second, there were temperature differences between the lakes, but when all decomposition rates were corrected to 20°C, control P. foliosus litter decomposed at nearly identical rates in both lakes (Figure 40), but oiled litter still decomposed much more rapidly in BL than in NFL (Figures 41 and 42). A third and most plausible explanation for interlake differences in crude oil impact is the physical differences between the lakes and the effects these differences have on mechanisms by which spilled crude oil can be reduced in quantity, displaced or altered in aquatic ecosystems (Atlas et al. 1978; Brooks et al. 1981; Blumer and Sass 1972; Larson et al. 1977, 1979; Westlake et al. 1977; Zürcher and Thüer 1978; Gearing et al. 1980; Hassett and Anderson 1979; Kolpack and Plutchak 1976; Knap and Williams 1982; Lee 1976; Myers 1976; Cretney et al. 1978; Lee et al. 1978; Owens 1978).

BL, which has a long wind fetch (maximum 32 km) and a largely unconsolidated sand bottom, is often disturbed by wind and waves. In situ visual observations confirmed that the litter substrates were constantly in contact with sand particles being moved about by wave action. Abrasion and sediment sorption of hydrocarbons were very likely reducing the oil coating on the P. foliosus litter, speeding its decomposition relative to its NFL counterpart. NFL is sheltered from the wind by high mountain ridges and has a consolidated sediment surface. The oil on plant litter in NFL was not removed by physical abrasion or sediment sorption. Thus, differences in the physical wind energy to the lakes and in sediment contact with the oiled plant litter between the lakes likely caused the different impact of crude oil on the decomposition of P. foliosus.

Interlake differences in the proportion of oiled litter decomposed relative to the proportion of control litter decomposed were not observed for T. latifolia. As stated previously, T. latifolia litter was not affected by an oil coating in the same manner as P. foliosus litter in either lake; therefore, parallel patterns for the two plant species between lakes were not expected. Additionally, oil permeated the leaf lacunae of T. latifolia and that portion of the oil was not exposed to the external environment which removed oil from the outer surfaces of litter in BL. Thus the

amount of oil associated with litter was more similar between lakes for T. latifolia than for P. foliosus, enhancing the similarity of oiled T. latifolia decompositional patterns between lakes. The extent of oil loss from T. latifolia was not significantly different between BL and NFL but was for P. foliosus (Table 29).

Aside from crude oils' effects, the rate of T. latifolia decomposition was quite different between lakes (Figure 40). Analysis of the factors contributing to this difference was not specifically addressed in the experimental design, but a hypothesis will be offered. T. latifolia litter contains a high proportion of refractory, structural compounds (Boyd 1968), which would require an acclimated decomposer community to oxidize. This plant does not occur naturally at the NFL experimental site, and it is possible that decomposers which could effectively degrade T. latifolia litter were also absent, perhaps causing unoiled litter from T. latifolia to degrade at a slower rate in NFL than in BL.

Regarding interlake differences of crude oil impacts; although, the effect of crude oil on the decomposition of P. foliosus was lessened in BL because of physical factors, this is not to imply that overall effects of oil pollution in that lake would be less than in NFL. Local effects of an oil spill would be reduced in BL because physical energy inputs would facilitate rapid removal of volatile toxic components by increasing evaporation of the crude oil (Atlas et al. 1978) and transporting some of the oil from the impacted site by water movement. However, the resulting dispersion would tend to increase the area of impact. Also, suspended sediments, which have a high affinity for many petroleum hydrocarbons (Myers 1976; Gearing et al. 1980; Knap and Williams 1982), would have greater contact with the spilled oil in a high energy system, such as BL. Oil polluted sediments tend to prolong the effects of oil because slow biodegradation (rather than more rapid physical means) becomes the major oil weathering process at that site (Prouse and Gordon 1976). Also, slow release of hydrocarbons from the sediments may become a source of chronic pollution to the overlying water (Teal et al. 1978). In NFL, the local and short-term effects of oil pollution would likely be more severe than in BL, but widespread and chronic problems would be less. Additionally, clean up would be more successful in a lake such as NFL where the spill would tend to remain localized.

Dissolved Oxygen Utilization

One of the most important environmental consequences of oil pollution is the added biological oxygen demand placed on the aquatic system. Petroleum hydrocarbons are biodegradable (Blumer and Sass 1972; Lee 1976; Atlas et al. 1978; Colwell et al. 1978; Cretney et al. 1978), and the degradation process requires oxygen. The added oxygen demand can be seen in this experiment by comparing the oxygen used per plant mass decomposed for oiled versus unoiled plants (Table 31). Jewell found that the above ratio ranged from 1.03 to 1.87 for 14 aquatic plants; his overall mean ratio was 1.30. In this study, the ratio for unoiled T. latifolia litter was 1.36 and 1.63 in BL and NFL respectively. Oiled T. latifolia litter had average ratios of 0.32 and 1.38 higher than unoiled litter in BL and NFL respectively. Assuming a reasonable littoral plant density of 500 g/m^2 (Wetzel 1975; Jewell 1971; Boyd and Hess 1970) and 10 percent biodegradation of these plants during ice cover, as occurred during this study, the additional oxygen demand due to oil would range from 16 to 69 g O_2/m^2. If the littoral region had an average depth of 2 m, 8 to 34.5 mg/l of additional dissolved oxygen would be utilized during the period of ice cover when oxygen would not be replenished from the atmosphere. This could lead to anoxic

conditions in the littoral region, or perhaps in the entire lake. Also, oxygen diffusion from the atmosphere to the water is restricted by an oil covering (Table 21) increasing the likelihood of low oxygen conditions during ice free periods.

The above hypothetical calculations are based solely on the results of this study. If an oil spill did occur and was extensive enough to coat the littoral vegetation as in this experiment, the added oxygen demand could be even higher than that calculated. The littoral vegetation would be killed suddenly and all the plant matter would enter the litter pool simultaneously, thus exerting a high oxygen demand due to rapid biodegradation of their labile compounds. As an illustration of what can happen, anoxic conditions persisted for several days in a small lake treated by a herbicide after aquatic plants entered the detritus pool en masse (Jewell 1971).

Control P. foliosus litter had an oxygen mass consumed to plant mass decomposed ratio of 0.73 in both lakes. This value is lower than the range reported by Jewell (1971). The difference likely resulted from high abiotic leaching of P. foliosus litter during initial phases of the experiment. Jewell (1971) assumed complete oxidation of all organic material in the litter when calculating his ratios. However, oxygen consumption for the plant material lost due to leaching in these experiments could not be included in the ratio because that portion of reduced organic material was removed from the site. Therefore, the ratio values obtained in this study for P. foliosus are lower.

BL oiled P. foliosus litter used oxygen at a rate similar to that of its unoiled counterpart. This lack of effect for the oil is at least partially caused by the loss of oil from BL litter by physical means. However, the oil removed from BL plant litter by sand abrasion and sediment sorption would be transported elsewhere and exert an oxygen demand on the lake at another site.

NFL oiled P. foliosus litter required from 1.73 to 2.75 grams more oxygen per gram of litter decomposed than did the unoiled controls. Using the plant density and littoral water depth assumed previously, the calculated oxygen utilization in the littoral region during an ice covered period due to oil is from 43.3 to 68.8 mg/l greater than the oxygen demand for decomposition of the plant litter alone. Thus, up to 4.8 times as much oxygen was required to oxidize oiled plant litter as that required to oxidize the same mass of unoiled plant litter (Table 31, NFL P. foliosus).

Nutrient Exchange Between Decomposing Plant Litter and Its Environment

Decomposition of aquatic vascular plants can be an important contributor to internal nutrient cycling where the littoral region is a substantial portion of the lake (Howard-Williams and Lenton 1975). In such lakes, one of the greatest impacts of crude oil pollution is likely to be its effect on the rate, extent, and distribution of nutrients released from decomposing plant litter. This research shows the rate and extent of nitrogen and phosphorus loss from P. foliosus to be reduced by WC.

Differences in nutrient loss values between unoiled and oiled litter might be explained by one or both of two factors. First, perhaps the litters' nutrient content differs at any given stage of decomposition between unoiled versus oiled litter; or second, the rate of decomposition between control and treatment litter differs. Results of the C:N and C:P ratios when plotted against the proportion of litter decomposed (Figure 49 and Table 36) indicate that the oil treatment had no effect on

the nutrient content of litter at any given stage of decomposition. The second factor, that of different decomposition rates, can explain the more rapid nutrient loss from the unoiled as compared to oiled litter. First order decay coefficients (K) for unoiled and oiled conditions at the various sites are shown in Table 35. Higher K values indicate more rapid litter decomposition. In general, rapid nutrient loss rates (shown in Figures 47-48) closely parallel higher K values. Thus, nutrient loss was simply a function of the rate of the litter's decomposition and was not otherwise affected by the oil.

Nutrient Content of Litter Throughout Time

The nutrient content of decomposing P. foliosus detritus, as measured by C:N and C:P ratios, was unaffected by crude oil. Past studies have stressed that the "quality" of detritus as a food source for heterotrophic organisms is a function of its nutrient content (Hunter 1976 and references within). Applying this criterion, crude oil did not alter the value of litter-derived detritus as an energy source for heterotrophs in this study. Some heterotrophic populations (specifically aquatic insects) were apparently inhibited by the oil associated with the detritus, however (Table 30). Detritus is central to the lake's metabolism by providing long term energy storage, that supports heterotrophic organisms during periods of limited autotrophic production, such as winters in temperate climates (Odum and de la Cruz 1963; Wetzel 1975; Rich and Wetzel 1978). In summary, oil does not adversely affect the function of litter as an energy source to heterotrophs, based on its phosphorus and nitrogen content. Oil, however, may make the energy less available to some heterotrophs because of its toxic or physical effects on the organisms.

Nutrient Release from Unoiled and Oiled Litter to Surrounding Water

The quantity of phosphorus and nitrogen lost from decomposing litter illustrates the litter's potential importance as an internal nutrient cycling agent. However, from an environmental perspective there is more interest in the nutrients which are actually released into the ambient water and the effect crude oil has on this process. The nutrients released to the lake ecosystem are most important because they are available to other organisms. In particular, if the nutrients are in inorganic form, the production of autotrophic organisms can be increased. Nutrients released from the littoral region of lakes are transported to the limnetic zone (Landers 1982; Carpenter 1980, 1981; Howard-Williams and Lenton 1975) where they may influence the metabolism of an entire lake.

The laboratory portion of this research was designed to assess the quantity of nutrients that could enter a lake ecosystem from decomposing litter and how crude oil affects that quantity. A large portion of the phosphorus lost from the unoiled litter was recovered in the aqueous medium as inorganic phosphorus (Table 38). Apparently, little of the phosphorus being released by decomposing unoiled litter was immobilized by decomposers. Furthermore, 85 to 88 percent of the phosphorus was released from unoiled litter as reactive, inorganic phosphorus directly capable of supporting autotrophic production. Carpenter (1980) found that about 90 percent of phosphorus released from decomposing Myriophyllum spicatum was inorganic.

A substantially lower portion of the phosphorus lost from oiled litter was recovered in the surrounding medium. Phosphorus immobilization by decomposers oxidizing the crude oil is the most

plausible explanation for the differences in phosphorus recovery from oiled versus unoiled litter. This contention is supported by the higher oxygen utilization rates by oiled litter. Additionally, there were high phosphorus concentrations on the oil which was associated with the litter after 35 days of the experiment due to phosphorus immobilization by decomposers. The fact that high phosphorus levels (this was not quantified) were associated with the crude oil also lends qualitative support to the contention that phosphorus was immobilized by decomposers oxidizing the oil. Crude oil provides a highly reduced organic carbon source to decomposers which can withstand its toxic effects. However, the crude oil used in this study (and most other crude oils) is deficient in critical nutrients (e.g., phosphorus and nitrogen) needed by the decomposer organisms. Therefore, nutrients must be supplemented by the environment if the crude oil is to be biologically oxidized. In this experiment, the phosphorus was supplied by the decomposing plant litter.

Lower recovery rates of inorganic phosphorus occurred for both control and oiled treatments in NFL when compared to BL. Perhaps the explanation is that higher phosphorus sorption occurred on NFL sediment. However, no differences in phosphorus concentration between lake sediments could be shown (Table 39). It is possible that the phosphorus sediment analyses performed were not sufficiently sensitive to detect the small difference in sediment phosphorus concentration required to explain the interlake phosphorus recovery difference (Appendix C). Therefore, higher sediment sorption of phosphorus by NFL sediment compared to BL sediment remains a potential but unverified explanation.

Inorganic nitrogen lost from oiled litter was completely immobilized before being released to the ambient water. Growing decomposer populations have a high nitrogen demand due to synthesis of proteins. As pointed out earlier, nitrogen required for oiled litter decomposition was partially supplied by the aqueous medium (fresh medium contained 80 µg/l total nitrogen). The amount of nitrogen required by the decomposers is illustrated by the fact that even the unoiled litter exerted a substantial nitrogen demand. Inorganic nitrogen recovered from the decomposing unoiled litter was only 21 percent of that lost by the litter. The nitrogen not recovered was assumed immobilized by the decomposer population denitrification, leading to nitrogen loss from the systems, was not likely important since aerobic conditions were maintained by diffuse aeration.

In short, a large portion of the nitrogen contained in P. foliosus litter was required by decomposers during the litter decomposition. High nitrogen demands by decomposers of plant litter have been noted by other researchers (Landers 1982; Nichols and Keeney 1973; Jewell 1971). The presence of oil increased this nitrogen demand significantly. Consequently, nitrogen may have limited the rate of oiled litter's decomposition.

Table 40 contains estimates of the quantities of nutrients that could be released to lake water by different littoral plant densities as calculated from the results of this study. Plant densities listed are within the range found in natural lakes (Wetzel 1975). Table 41 shows levels of external nutrient loading which are considered permissible or dangerous to a lake's present trophic state. Comparisons between the two show that, nutrient loading (particularly of phosphorus) in the littoral region of a lake due to macrophytic decomposition can be large enough to be classified as dangerous. However, since only a portion of most lakes is littoral, the loading to a given lake due to litter decay must be adjusted to account for that portion of the lake outside the littoral region. Dangerous loading values in Table 41 are listed for a 55-day and 1-year period;

Table 40. Nutrient release values at various hypothetical plant densities.

Hypothetical Plant Density g/m^2	Bear Lake				New Fork Lake			
	Unoiled Litter		Oiled Litter		Unoiled Litter		Oiled Litter	
	N	P	N	P	N	P	N	P
	(g Nutrient Released/m^2/ 55 d)							
50	0.4	0.15	0	0.10	0.4	0.11	0	0.03
100	0.8	0.30	0	0.20	0.8	0.21	0	0.05
200	1.6	0.47	0	0.40	1.5	0.42	0	0.10
350	2.7	1.04	0	0.70	2.7	0.74	0	0.18
500	3.9	1.5	0	1.0	3.9	1.1	0	0.25
650	5.0	1.9	0	1.3	5.0	1.4	0	0.33

All values are based on nutrient loss from P. foliosus litter during its first 55 days of decomposition in the lakes and the proportion of lost nutrients which were released to the ambient water in inorganic form as determined by laboratory experimentation.

Table 41. Values for permissible and dangerous loading of nitrogen and phosphorus in lakes of varying depths.

Mean Lake Depth (m)	Permissible Loading (g/m^2 y)		Dangerous Loading (g/m^2 y)		Dangerous Loading (g/m^2/55 d)	
	N	P	N	P	N	P
5	1.0	0.07	2.0	0.13	0.30	0.02
10	1.5	0.10	3.0	0.20	0.45	0.03
50	4.0	0.25	8.0	0.50	1.21	0.08
100	6.0	0.40	12.0	0.80	1.81	0.12

Source: Wetzel (1975); Vollenweider (1968)

nutrient release rates decline over a decompositional cycle, so the rate over the first 55 days would not be equaled during the remainder of a year's decomposition period.

The intent of the above comparison is not to argue that aquatic vascular plant decay is potentially dangerous to the trophic state of a lake, but rather to show that the magnitude of nutrient input by decaying vascular plants can be substantial. In a balanced lake (one not affected by cultural eutrophication), nutrients released from vascular plant decomposition are needed to maintain the level of production in the lake. Impacts, such as oil pollution, which immobilize these nutrients at their source, tend to have an unbalancing effect. For example, if primary production was reduced due to nutrient limitation, the existing production of upper trophic levels would also be reduced. In this way, oil pollution may affect the whole water body even if the oil is not present over the whole lake.

In lakes affected by cultural eutrophication, it might seem desirable for the nutrients released from decomposing vascular plant litter to be immobilized at their source. However, one of the severe problems in eutrophic lakes is oxygen depletion as a result of organic material decay. In the event of oil pollution, the oxygen demand will continue; the source being allochthonous petroleum hydrocarbons rather than autochthonous products of primary production. In fact, oxygen depletion might be intensified because primary production in the system would be reduced due to nutrient limitation and the oxygen normally supplied by primary producers would not be available to offset oxygen consumption by petroleum decomposers. In short, oil pollution can change the nutrient dynamics of a lake system regarding the vascular aquatic plants in ways that are harmful to the oxygen balance and trophic structure of a lake.

CONCLUSIONS AND RECOMMENDATIONS

Conclusions

Impacts of South Louisiana and Wyoming Crude oils on the decomposition of Typha latifolia and Potamogeton foliosus litter in Bear and New Fork Lakes were investigated in situ and in laboratory experiments. The following conclusions are based on results of these studies:

1. The decomposition model; $w = w_o e^{(K_o/a)(e^{-at}-1)}$ described litter decomposition over a year's period in this study.

2. The rate and extent of T. latifolia litter decomposition was reduced by oil addition in BL and NFL over a year's period.

3. The rate of P. foliosus litter decomposition was reduced by oil addition in BL and NFL.

4. The activity of decomposer communities (as measured by dissolved oxygen utilization) associated with oiled litter was from 1.2 to 1.5 times greater than corresponding unoiled litter in NFL; the same measurement for oiled litter in BL was 1.0 to 1.1 times that of unoiled litter. Crude oil had no apparent toxic effects on the overall decomposer community, even within the first 3 days after exposure to fresh crude oil.

5. Decomposition rates corrected to 20°C indicated that oil had a greater effect on the decomposition of P. foliosus in NFL than in BL. Based on temperature corrected rates, from 30 to 34 percent of oiled litter would remain in NFL after 365 days but only 3 to 9 percent would remain after that period in BL.

6. Decomposition rates corrected to 20°C for T. latifolia indicated than even unoiled litter from this plant decomposed more rapidly in BL than in NFL (24 percent of the original litter would remain in BL, and 40 percent in NFL, after 365 days).

7. Oil was lost more rapidly from P. foliosus litter in BL than in NFL, but oil was lost at roughly the same rate from T. latifolia litter in both lakes.

   a. Differences in rates of oil loss from plant litter are explained by a combination of plant structural differences and differences between lakes. BL has higher wind derived physical energy input and a greater incidence of suspended sediments because of its unconsolidated sediment surface than does NFL.

   b. T. latifolia has more intricate internal structure than P. foliosus, which isolated trapped crude oil from the external environment in the former plant's litter.

8. Oxygen consumed per plant mass decomposed was from 1.2 to 4.8 times higher for oiled litter than for unoiled litter considering both lakes and both plant species.

9. Nutrient loss was generally less for oiled plant litter than for unoiled litter, primarily due to a reduction in the rate of oiled-litter decomposition.

10. From 69 to 91 percent of the phosphorus lost from decomposing unoiled plant litter was released to the

environment in an inorganic form whereas that percentage was only 17-57 for oiled litter.

11. Twenty-one percent of the nitrogen lost from decomposing unoiled plant litter was released to the environment in an inorganic form, but nitrogen was actually removed from the environment during oiled plant decomposition.

a. Nitrogen limitation is the most probable explanation for the rapidly decreasing rates of oiled litter decomposition through time.

b. Nutrient immobilization by oil oxidizing decomposers is the most reasonable explanation for the reduction of nutrient release to the environment from oiled plant litter.

12. C:N and C:P ratios (common indices of litter quality as an energy source for heterotrophs) were not affected by the oil coating at any stage of decomposition.

13. Oil coating on plant litter restricted invertebrate populations even after a year of oil weathering in both BL and NFL.

Recommendations for Additional Research[a]

1. The effects of varying concentrations of crude oils on aquatic ecosystems need additional research. Experiments, such as those of this study, can be employed to determine critical oil pollutant levels.

2. Detailed experiments are needed to determine the magnitude and duration of adverse effects to aquatic ecosystems after their sediments are contaminated by crude oil. Sediments recently contaminated with oil and those allowed to weather *in situ* for various time durations after contamination could be used in three phase microcosm studies to determine the adverse effects.

3. The effects of lake-specific physical elements, such as sediment type and energy input, on crude oil weathering need further study. Specifically, the extent that physical factors alter effects of crude oil in aquatic ecosystems should be determined.

4. Physical effects of crude oil, such as its inhibitory effects on gas diffusion and physiological effects of oil coating on plant and animal surfaces, should be studied *in situ* (*in situ*, so natural weather factors are present to ameliorate physical effects of the oil).

5. Investigations exploring crude oil effects at different water hardnesses should be continued. Microcosm experiments containing a common sediment and biological inoculum with water hardness as the only variable are recommended to meet this objective.

6. Further definition of crude oils' relative effects on different groups of freshwater organisms and function groups of organisms is needed.

Engineering Significance: Recommendations to Control Oil Spills on Lakes

1. Obviously, the best control method is to prevent crude oil from entering lakes. The research indicates that long-term deleterious effects could result in a lake impacted by crude oil. Stringent safeguards should be employed to avoid oil spills in lakes.

2. In the event of an oil spill, the spill should be contained and as much oil as possible should be removed from the lake as soon as possible. Removal of the oil would lessen long-

[a]These recommendations are in order of their priority.

term effects, such as increased oxygen demand, nutrient immobilization, and sediment contamination.

3. The use of dispersants on a lake oil spill is not advised; the dispersant would not confront environmental problems caused by the oil, but would tend to cause the oil contamination to be more widespread and harder to remove from the lake. Dispersants are more appropriately used in large water bodies, such as oceans, which have greater assimilatory capacity than smaller water bodies, such as lakes.

4. Certain lake and crude oil characteristics are important in determining effects of oil pollution. To prepare for a possible accident in advance, the following lake and oil characteristics should be investigated.

Lake characteristics:

a. A range of wind energy inputs that could be expected at sites where spills are most likely, and the extent and speed that oil would be transported from the impacted site.

b. Critical areas in the lake (e.g. fish spawning sites) and the conditions under which spilled oil would impact such sites.

c. The extent that sediments of the lakes are suspended at potential accident sites and the affinity the sediments there have for petroleum hydrocarbons.

Crude oil characteristics:

a. Composition of petroleum hydrocarbons in the crude oil.

b. Solubility of the crude oil in the lake's water.

c. Levels at which crude oil are toxic to the lake's biota and how long the toxicity persists.

d. Rates of oxygen utilization and nutrient immobilization of contaminated water and sediment.

e. Rates of evaporation of petroleum hydrocarbons under natural conditions.

Based on the type of information listed above a pollution control program, which would minimize environmental damage in the event of an oil spill, could be formulated prior to a spill.

5. After an oil spill, the following parameters could be monitored to assess the continuing impact of oil pollution and the need for additional clean up, or other pollution control measures. The same parameters could also be measured before an accident occurs so background levels within the water body are known.

a. Petroleum hydrocarbon identity and concentration within the water column and at the sediment surface.

b. Dissolved oxygen concentration within the water column.

c. Redox potential at the sediment surface.

d. Oxygen demand placed on the system by organic compounds within the water column and at the sediment surface.

e. Productivity:respiration ratio (P/R) within the water column and at the sediment surface.

f. Nutrient (particularly nitrogen and phosphorus) concentrations and availability within water column and at the sediment surface.

g. Nutrient demand placed on the system because of the degradation of crude oil compounds.

h. Bioassay tests, using ambient lake water and nutrient amendments, to determine when toxic effects cease to exist to various groups of organisms of the lake.

i. Bacteria enumeration within the water column and at the sediment surface.

j. Algae identification and enumeration within the water column and at the sediment surface.

k. Invertebrate identification and enumeration within the water column and at the sediment surface.

l. Species diversity of algae and invertebrates at the oil spill site.

Items a, b, c, f, h, i j, and k would be helpful in assessing the current status of the environment, whereas d, e, and g would be valuable for projecting future trends and ongoing impacts of the oil.

6. The following continuing oil pollution control measures might be suggested by the information gained in a monitoring program as being needed subsequent to the initial crude oil clean up effort (item #2).

a. Addition of critical nutrients (e.g. N, P, and perhaps some trace nutrients) to the impacted site if toxic effects of the oil on autotrophs has subsided and nutrient immobilization by oil degrading organisms is causing low P:R ratios or low dissolved oxygen conditions. The added nutrients would increase primary production, which would be a source of oxygen to the impacted site. Also, the added nutrients would accelerate oil weathering by increasing the rate of the oil's biological degradation (if nutrients were limiting that process). Before employing this control measure, consideration should be given to the ramifications of nutrient addition on the lake's tropic state. Nutrient addition should be limited in scale and employed only at problem sites. A justification for nutrient addition might be to avoid the destruction of the lake's sediments oxidized microzone, or to avoid low oxygen conditions in the water which would destroy fish, and other aquatic biota, populations.

b. Dredging sediments and/or removing oil coated vascular aquatic plants contaminated by crude oil. This measure would reduce subsequent problems related to increased oxygen utilization and nutrient immobilization by physically removing oil from the site. Such environmental disturbances must be justified by a substantial quantity of oil being removed from the polluted site.

c. Stimulation of natural oxygen diffusion, or artificial addition of oxygen, to the oil polluted site. Encouragement of natural oxygen diffusion by disruption of ice cover over the polluted site or dissipation of an oil covering at the water surface should be employed. In extreme cases artificial agitation at the water surface to increase oxygen diffusion or direct oxygen addition to the water within a limited area may be necessary.

7. Many aspects of these recommendations can also be applied in controlling oil pollution in other aquatic ecosystems, such as streams, rivers, and marine habitats.

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APPENDICES

Appendix A

Techniques for Microcosm Studies

Table A-1. Techniques used for water and sediment chemical analyses during microcosm experiments.

Analytic Procedure	Method	Source
Water		
pH	Potentiometric	APHA 1980
Alkalinity	Potentiometric Titration	APHA 1980
Total Hardness	EDTA Titrimetric	APHA 1980
Calcium	EDTA Titrimetric	APHA 1980
Dissolved Oxygen	Winkler with Azide Modification	APHA 1980
Total Organic Carbon	Combustion Infrared	APHA 1980
Nitrate	Cadmium Reduction	APHA 1980
Nitrite	Diazotization	APHA 1980
Ammonia	Indophenol	APHA 1980
Total Phosphorus	Acid-Persulfate Digestion	APHA 1980
Orthophosphorus	Ascorbic Acid	APHA 1980
Sediment		
Total Phosphorus	Acid-Persulfate Digestion	APHA 1980
Nitrate	KCl-Extraction-Cd Reduction	Bremmer 1965
Nitrite	KCl-Extraction-Diazotization	Bremmer 1965
Ammonia	KCl-Extraction-Indophenol	Bremmer 1965
Volatile Content	Combustion at 550°C	APHA 1980

Table A-2. Miscellaneous techniques performed on Bear Lake microcosms.

Bacterial Enumeration: Standard plate count media used. Three replicates were done at each of three dilutions (0.1, 0.01, 0.001) and means calculated at the dilution which had bacteria counts between 30 and 300 (APHA 1980).

Invertebrate Enumeration: One liter of the aqueous phase removed from a given microcosm was filtered through a GF/C glass fiber filter and invertebrates collected on the filter were counted under a dissecting microscope.

Relative Fluorescence: One liter of the aqueous phase removed from a given microcosm (with a small amount of $MgCO_3$ added) was filtered through a GF/C glass fiber filter, the filter was submerged in 10 ml 90 percent acetone and maintained in a dark refrigerator for 24 hours, then relative fluorescence of the acetone was determined on a Turner Model 111 Fluorometer (APHA 1980).

Appendix B

Microcosm Mass Balance Program

Table B-1. Micro-4, the computer program used for mass balance calculations of microcosm data.

```
0   FILE  1(KIND=DISK,TITLE="RANREWRITE",PROTECTION=SAVE)
1    $ RESET FREF
2   FILE  11(KIND=DISK,TITLE="F11",PROTECTION=SAVE,FILETYPE=7)
3   FILE  12(KIND=DISK,TITLE="F12",PROTECTION=SAVE,FILETYPE=7)
4   FILE  13(KIND=DISK,TITLE="F13",PROTECTION=SAVE,FILETYPE=7)
5   FILE  14(KIND=DISK,TITLE="F14",PROTECTION=SAVE,FILETYPE=7)
6   FILE  15(KIND=DISK,TITLE="F15",PROTECTION=SAVE,FILETYPE=7)
7   FILE  16(KIND=DISK,TITLE="F16",PROTECTION=SAVE,FILETYPE=7)
8   FILE  17(KIND=DISK,TITLE="F17",PROTECTION=SAVE,FILETYPE=7)
9   FILE  18(KIND=DISK,TITLE="F18",PROTECTION=SAVE,FILETYPE=7)
10  FILE  19(KIND=DISK,TITLE="F19",PROTECTION=SAVE,FILETYPE=7)
11  FILE  20(KIND=DISK,TITLE="F20",PROTECTION=SAVE,FILETYPE=7)
12  FILE  21(KIND=DISK,TITLE="F21",PROTECTION=SAVE,FILETYPE=7)
13  FILE  22(KIND=DISK,TITLE="F22",PROTECTION=SAVE,FILETYPE=7)
14  FILE  23(KIND=DISK,TITLE="F23",PROTECTION=SAVE,FILETYPE=7)
15  FILE  24(KIND=DISK,TITLE="F24",PROTECTION=SAVE,FILETYPE=7)
16  FILE  25(KIND=DISK,TITLE="F25",PROTECTION=SAVE,FILETYPE=7)
17  FILE  26(KIND=DISK,TITLE="F26",PROTECTION=SAVE,FILETYPE=7)
18  FILE  27(KIND=DISK,TITLE="F27",PROTECTION=SAVE,FILETYPE=7)
19  FILE  28(KIND=DISK,TITLE="F28",PROTECTION=SAVE,FILETYPE=7)
20  FILE  29(KIND=DISK,TITLE="F29",PROTECTION=SAVE,FILETYPE=7)
21  FILE  30(KIND=DISK,TITLE="F30",PROTECTION=SAVE,FILETYPE=7)
22  FILE  31(KIND=DISK,TITLE="F31",PROTECTION=SAVE,FILETYPE=7)
23  FILE  32(KIND=DISK,TITLE="F32",PROTECTION=SAVE,FILETYPE=7)
24  FILE  33(KIND=DISK,TITLE="F33",PROTECTION=SAVE,FILETYPE=7)
25  FILE  34(KIND=DISK,TITLE="F34",PROTECTION=SAVE,FILETYPE=7)
26  FILE  35(KIND=DISK,TITLE="F35",PROTECTION=SAVE,FILETYPE=7)
27  FILE  36(KIND=DISK,TITLE="F36",PROTECTION=SAVE,FILETYPE=7)
28  FILE  40(KIND=DISK,TITLE="NEW8",PROTECTION=SAVE,FILETYPE=7)
29  C**
30  C**
31  C**   PROGRAM MICRO FOR THE MASS BALANCING OF
32  C**   MICROCOSM GASES,NUTRIENTS AND/OR MAJOR
33  C**   ELEMENTS. THIS PROGRAM IS ADJUSTED FOR--
34  C**
35  C***      ****************************************
36  C**   * OIL INTRUSION MICROCOSM STUDY 1981    *
37  C**   ****************************************
38  C*
39  C*    * INVESTIGATING THE INTERACTIONS OF
40  C*     CRUDE OIL IN BEAR
41  C**    LAKE SIMULATED MICROCOSMS
42  C*      IN RESPONSE TO A ONETIME APPLICATION OF OIL
43  C*
44  C**    * NET OXYGEN PRODUCTION AND CONSUMPTION
45  C*      IN LITTORAL AND HYPOLIMNETIC ENVIRONS
46  C*
47        DIMENSION P(200),RT(200),XNO(25,24,2),XGO(12,24,2),TI(200,24)
48       *,VINI(200,24),VOLG(24),Y(24),TO(200,24),F(200,24),YGAS(200,24)
49       *,VOGSTP(200,24),XMGASO(12,24),XMGASA(12),XMGASG(12),GASNET(12)
50       *,FA(12),XIN1(25),XIN2(12,24) ,XMGPRE(200,24)
51       *,HEGAS(200,24),HEAQU(200,24),MINO(24)
52       *,VNET(200,24),AQAOJ(12),DXNO(25,24),DXGO(12,24),XMGASI(12),Z(12)
53       *,PROT(24),HYDRX(24),ALFO(24),ALFONE(24),ALFTWO(24),VOLW(24),CTOOO(
54       *24),AQCOO(24),ALK(24),XINNO3(24),XINNH3(24)
55        DATA IOUMX/1HX/
56  C*
57  C*    DEFINITION OF XNO(KN,J,IST) VARIABLES
58  C*    KN=1   TOTAL ALKALINITY                    MG/L AS CACO3
59  C*    KN=2   TOTAL HARDNESS   MG/L AS CACO3
60  C*    KN=3   PH
61  C*    KN=4   DISSOLVED OXYGEN                    MG/L
62  C*    KN=5   PHOSPHORUS,TOTAL                    MG/L
63  C*    KN=6   PHOSPHORUS,ORTHO                    MG/L
64  C*    KN=7   CALCIUM HARDNESS      MG/L AS CACO3
65  C*    KN=8   MAGNESIUM HARDNESS    MG/L AS CACO3
66  C*    KN=9   NITRATE                MG/L
67  C*    KN=10  NITRITE                             MG/L
68  C*    KN=11  AMMONIA                             MG/L
69  C*    KN=12  TOTAL ORGANIC CARBON                          MG/L
70  C*    KN=13  TOTALINORGANIC C*, ALKALINITYMG/L AS CACO3
71  C*    KN=14  HYDROXIDE ALKALINITY                MG/L AS CACO3
72  C*    KN=16  -LOG(CT)
```

Table B-1. Continued.

```
C*    KN=15  CT , TOT. INORG. CARBON        MOLES/L
C*    KN=17  HYDROGEN ION CONC.             MOLES/L
C*    KN=18  AQUEOUS H2CO3*                 MOLES/L
C*    KN=19  -LOG(H2CO3*)
C*
C*
C*    LOOP TO SET HEADINGS ON OUTPUT FILES
      DO 1113 IZ=1,12
      IVAL=10+IZ
      WRITE(IVAL,1115)
 1115 FORMAT(1X,"INT",1X,"DAY",3X,"VNET",6X,"H2",6X,"O2",5X,"CO2"
     *,5X,"CH4",6X,"HE",5X,"DTP",5X,"DOP",4X,"DNO3",4X,"DNH3",6X,"DN")
 1113 CONTINUE
      DO 1114 IY=1,12
      KVAL=22+IY
      WRITE(KVAL,1116)
 1116 FORMAT("INT",1X,"DAY",4X,"TA",3X,"TH",2X,"PH",2X,"DO",6X,"P",5X,
     *"OP",3X,"CA",3X,"MG",4X,"NO3",4X,"NO2",4X,"NH3",2X,"TOC",2X,"TIC",
     *2X,"OHA",4X,"-LOGCT",7X,"TIC",6X,"MCONC",5X,"H2CO3",1X,
     *"-LOGH2CO3")
 1114 CONTINUE
C*                                  STEP 1    INITIALIZE COUNTERS AND READ
C*                                            INITIAL CONDITIONS
C*
      READ(40,500)NMICRO,NNUTI,NNUTO,NGASI,NGASO,IOPT,EKW,EKONE,EKTWO
  500 FORMAT(6I5,3E10.4)
      IF(IOPT.GT.0) WRITE(1,600) NMICRO,NNUTI,NNUTO,NGASI,NGASO,IOPT,EKW
     *,EKONE,EKTWO
      WRITE(35,*) NMICRO,NNUTI,NNUTO,NGASI,NGASO,IOPT,EKW,EKONE,EKTWO
  600 FORMAT(1H1,6I5,3E10.4)
      READ(40,605) (MINO(L),L=1,NMICRO)
  605 FORMAT(16I5)
      IF(IOPT.GT.0) WRITE(1,606)(MINO(L),L=1,NMICRO)
      WRITE(35,*) (MINO(L),L=1,NMICRO)
  606 FORMAT(1H ,16I5)
C*
      READ(40,607) (VOLW(L),L=1,NMICRO)
  607 FORMAT (12F5.0)
C*                                  STEP 1.1
C*
      IST=1
      IED=2
      INT=0
      IOS=0
      VOLA=1.0
C*
C*                                  STEP 1.2
C*
      READ(40,501) P(1),RT(1)
      IF(IOPT.GT.0) WRITE(1,601) P(1),PT(1)
      WRITE(35,*) P(1),RT(1)
  601 FORMAT(1H ,14F9.4 / 1H ,1E9.4,4F9.4,2E9.4,1F9.4)
      DO  1 L=1,NMICRO
      J=MINO(L)
      F(1,J)=1.0
C*
C*                                  STEP 1.3
C*
      READ(40,501) (XNO(KN,J,IST),KN=1,12)
  501 FORMAT(12F5.0)
      DIFF=(XNO(3,J,IST))-14.0
      XNO(14,J,IST)=5.0E+04*10**(DIFF)
      XNO(13,J,IST)=(XNO(1,J,IST)-XNO(14,J,IST))
      ALK(J)=(XNO(13,J,IST)/50000)
      PROT(J)=10**(-XNO(3,J,IST))
      HYDRX(J)=EKW/PROT(J)
       ALFO(J)=PROT(J)**2/(PROT(J)**2+EKONE*PROT(J)+EKONE*EKTWO
       ALFONE(J)=PROT(J)*EKONE/(PROT(J)**2+EKONE*PROT(J)+EKONE*EKTWO
        ALFTWO(J)=EKONE*EKTWO/(PROT(J)**2+EKONE*PROT(J)+EKONE*EKTWO
      CTOO(J)=(ALK(J)-HYDRX(J)+PROT(J))/(ALFONE(J)+2.0*ALFTWO(J))
      AQCO0(J)=ALFO(J)*CTOO(J)
      XNO(15,J,IST)=CTOO(J)
      XNO(16,J,IST)=-(ALOG10(CTOO(J)))
      XNO(17,J,IST)=PROT(J)
      XNO(18,J,IST)=AQCO0(J)
```

Table B-1. Continued.

```
148           XNO(19,J,IST)=-(ALOG10(AGCNO(J)))
149           IF(IOPT.GT.0) WRITE(1,601) (XNO(KN,J,IST),KN=1,NNUTO)
150           WRITE(35,*/) (XNO(KN,J,IST),KN=1,NNUTO)
151     C*
152     C*
153     C*                                    STEP 1.4
154
155           READ(40,501) (XGO(KG,J,IST),KG=1,NGASO)
156           IF(IOPT.GT.0)  WRITE(1,601) (XGO(KG,J,IST),KG=1,NGASO)
157           WRITE(35,*/) (XGO(KG,J,IST),KG=1,NGASO)
158     C*
159     C*                                    STEP 1.5
160
161           READ(40,501) TI(1,J),VINI(1,J),HE
162           IF(IOPT.GT.0) WRITE(1,601) TI(1,J),VINI(1,J),HE
163           WRITE(35,*/) TI(1,J),VINI(1,J),HE
164     C*
165     C*                                    STEP 1.6
166
167           VP=FVP(TI(1,J))
168           Y(J)=(P(1)/760.)*HE/((273.15+RT(1))*82.06)
169     C*
170     C*                                    STEP 1.7
171
172           VINI(1,J)=((P(1)-VP)/760.)*(VOLG(J)+VINI(1,J))*273.15/
173          *(273.15+TI(1,J)) -Y(J)*22415.
174           VOGSTP(1,J)=VINI(1,J)
175         1 CONTINUE
176     C*
177     C*                                    STEP 2     READ DAILY INPUT DATA AND
178     C*                                               CALCULATE THE NET CHANGE IN
179     C*                                               GAS VOLUME AT STP OVER A ONE
180     C*                                               DAY PERIOD
181     C*
182         5 INT=INT+1
183     C*
184     C*                                    STEP 2.1
185     C*
186           READ(40,510,END=99) NDAYS ,IDUM
187         510 FORMAT(I5,A1)
188           IF(IOPT.GT.0) WRITE(1,602) NDAYS
189           WRITE(35,*/) NDAYS,IDUM
190           IF(IDUM.NE.IDUMX) GO TO 98
191         602 FORMAT(1H ,8I5)
192           XDAYS=NDAYS
193           NDP1=NDAYS+1
194           DO 10 ID=2,NDP1
195           READ(40,501) P(ID),RT(ID)
196           IF(IOPT.GT.0) WRITE(1,601) P(ID),RT(ID)
197           WRITE(35,*/) P(ID),RT(ID)
198           DO 11 L=1,NMICRO
199           J=MINO(L)
200     C*
201     C*                                    STEP 2.2
202     C*
203           READ(40,501) TI(ID,J),TO(ID,J),CR,VADJ,F(ID,J),HE
204           IF(IOPT.GT.0) WRITE(1,601) TI(ID,J),TO(ID,J),CR,VADJ,F(ID,J),HE
205           WRITE(35,*/) TI(ID,J),TO(ID,J),CR,VADJ,F(ID,J),HE
206           IF(F(ID,J)-1.0E-6) 2,3,3
207         2 F(ID,J)=1.0
208     C*
209     C*                                    STEP 2.3
210     C*
211         3 VADD=HE*(P(ID)/760.)/((273.15 +RT(ID))*82.06)
212           VP=FVP(TO(ID,J))
213           V=((P(ID)-VP)/760.)*(VOLG(J)+CR)*273.15/(273.15+TO(ID,J))
214           VG=Y(J)/(1.0+(82.06*273.15*4.0E-3)/(CR*VOLG(J)))
215           VA=Y(J)-VG
216           MEGAS(ID,J)=VG*22415.
217           MEAQU(ID,J)=VA*22415.
218           VOGSTP(ID,J)=V-MEGAS(ID,J)
219           VNET(ID,J)=VOGSTP(ID,J)-VINI(ID-1,J)
```

Table B-1. Continued.

```
C*
C*                                  STEP 2.4
C*
      IF(ABS(VADJ).GT.0.00001) GO TO 405
      VINI(ID,J)=VOGSTP(ID,J)
      GO TO 410
  405 IF(VADD.GT.1.0E-7) GO TO 420
      VG=VG*(VADJ+VOLG(J))/(CR+VOLG(J))
      R=((P(ID)-VP)/760.)*(VOLG(J)+VADJ)*273.15/(273.15+TO(ID,J))
      VINI(ID,J)=R*VG*22415.
      GO TO 410
  420 VINI(ID,J)=VOGSTP(ID,J)
  410 Y(J)=VADD+VG+VA*(10.7-F(ID,J))/10.7
   11 CONTINUE
   10 CONTINUE
C*
C*                                  STEP 3    READ INPUT DATA AT THE END
C*                                            OF THE INTERVAL AND INTERPOLATE
C*                                            BETWEEN THE BEGINNING AND END
C*                                            OF THE INTERVAL TO ESTIMAT THE
C*                                            AVERAGE DAILY CHANGE IN
C*                                            CONSTITUENT CONCENTRATIONS.
C*
      DO 12 L=1,NMICRO
      J=MINO(L)
C*
C*                                  STEP 3.1
C*
      READ(40,501) (XNO(KN,J,IED),KN=1,12)
      DIFF=(XNO(3,J,IED))-14.0
      XNO(14,J,IED)=5.0E+04*10**(DIFF)
      XNO(13,J,IED)=(XNO(1,J,IED)-XNO(14,J,IED))
      ALK(J)=(XNO(13,J,IED)/50000)
      PROT(J)=10**(-XNO(3,J,IED))
      HYDRX(J)=EKW/PROT(J)
      ALFO(J)=PROT(J)**2/PROT(J)**2+EKONE*PROT(J)+EKONE*EKTWO
      ALFONE(J)=PROT(J)*EKONE/PROT(J)**2+EKONE*PROT(J)+EKONE*EKTWO
      ALFTWO(J)=EKONE*EKTWO/PROT(J)**2+EKONE*PROT(J)+EKONE*EKTWO
        CTCOO(J)=(ALK(J)-HYDRX(J)+PROT(J))/(ALFONE(J)+2.0*ALFTWO(J))
      AQCOO(J)=ALFO(J)*CTCOO(J)
      XNO(15,J,IED)=CTCOO(J)
      XNO(17,J,IED)=PROT(J)
      XNO(18,J,IED)=AQCOO(J)
      WRITE(35,*/) (XNO(KN,J,IED),KN=1,NNUTO)
      IF(IOPT.GT.0) WRITE(1,601) (XNO(KN,J,IED),KN=1,NNUTO)
C*
C*                                  STEP 3.2
C*
      READ(40,501) (XGO(KG,J,IED),KG=1,NGASO)
      WRITE(35,*/) (XGO(KG,J,IED),KG=1,NGASO)
      IF(IOPT.GT.0)  WRITE(1,601) (XGO(KG,J,IED),KG=1,NGASO)
   12 CONTINUE
      WRITE(1,999)
  999 FORMAT(1H ,4X,"IFILE",2X,"INTERVAL",3X,"DAY",8X,"VNET",9X,
     *"NITROGAS",8X,"OXYGAS",11X,"CO2",9X,"METHANE",7X,
     */30X,"TOTAL PHOS",4X,"ORTHO PHOS",6X,"NITRATE",8X,
     *"AMMONIA",7X,"INORG, N")
      DO 15 L=1,NMICRO
      J=MINO(L)
C*
C*                                  STEP 3.3
C*
      DO 16 KN=1,NNUTO
      DXNO(KN,J)=(XNO(KN,J,IED)-XNO(KN,J,IST))/XDAYS
   16 CONTINUE
C*
C*                                  STEP 3.4
C*
      DO 17 KG=1,NGASO
      DXGO(KG,J)=(XGO(KG,J,IED)-XGO(KG,J,IST))/XDAYS
```

Table B-1. Continued.

```
      17 CONTINUE
      15 CONTINUE
C*
C*                                  STEP 4     CALCULATE THE INITIAL MASSES OF
C*                                             THE GASES IN EACH MICROCOSM FOR
C*                                             THE FIRST DAY OF THE FIRST
C*                                             INTERVAL
C*
        IF(IDS.GT.0) GO TO 23
        DO 22 L=1,NMICRO
        J=MINO(L)
C*
C*                                  STEP 4.1
C*
        DO 21 KG=1,NGASO
        RK=FRK(KG,TI(1,J))
        XMGPRE(KG,J)=10.29*55.5*Z(KG)*P(1)*XGO(KG,J,IST)/RK
        XMGASO(KG,J)=VOGSTP(1,J)*XGO(KG,J,IST)*Z(KG)/22415.*XMGPRE(KG,J)
      21 CONTINUE
      22 CONTINUE
      23 CONTINUE
C*
C*                                  STEP 5     PERFORM MASS BALANCES ON EACH
C*                                             MICROSOSM FOR EACH DAY IN THE
C*                                             INTERVAL AND WRITE OUTPUT ON
C*                                             DISK.
C*
        DO 20 ID=2,NDP1
        IDS=IDS+1
        DO 30 L=1,NMICRO
        J=MINO(L)
C*
C*                                  STEP 5.1
C*
        DO 40 KG=1,NGASO
        XGO(KG,J,IST)=XGO(KG,J,IST)+DXGO(KG,J)
        RK=FRK(KG,TO(ID,J))
        XMGASA(KG)=10.29*55.5*Z(KG)*XGO(KG,J,IST)*P(ID)*
       $(VOGSTP(ID,J)/VOGSTP(ID,J) +MEGAS(ID,J))/RK
        AGAOJ(KG)=XMGASA(KG)-XMGPRE(KG,J)
        XMGPRE(KG,J)=XMGASA(KG)
        XMGASG(KG)=VOGSTP(ID,J)*XGO(KG,J,IST)*Z(KG)/22415.
C*
C*                                  STEP 5.2
C*
        GASNET(KG)=XMGASA(KG)+XMGASG(KG)-XMGASO(KG,J)
C*
C*                                  STEP 5.3
C*
        RK=FRK(KG,TI(ID,J))
        XMGASI(KG)=F(ID,J)*55.5*Z(KG)*P(ID)*FA(KG)/RK
        XMGASO(KG,J)=VINI(ID,J)*XGO(KG,J,IST)*Z(KG)/22415. *
       $XMGASI(KG)+(10.29-F(ID,J))*XMGASA(KG)/10.29
      40 CONTINUE
C*                                  STEP 5.4
        XNO( 1,J,IST)=XNO( 1,J,IST)+DXNO( 1,J)
        XNO( 2,J,IST)=XNO( 2,J,IST)+DXNO( 2,J)
        XNO( 3,J,IST)=XNO( 3,J,IST)+DXNO( 3,J)
        XNO( 4,J,IST)=XNO( 4,J,IST)+DXNO( 4,J)
        XNO( 5,J,IST)=XNO( 5,J,IST)+DXNO( 5,J)
        XNO( 6,J,IST)=XNO( 6,J,IST)+DXNO( 6,J)
        XNO( 7,J,IST)=XNO( 7,J,IST)+DXNO( 7,J)
        XNO( 8,J,IST)=XNO( 8,J,IST)+DXNO( 8,J)
        XNO( 9,J,IST)=XNO( 9,J,IST)+DXNO( 9,J)
        XNO(10,J,IST)=XNO(10,J,IST)+DXNO(10,J)
        XNO(11,J,IST)=XNO(11,J,IST)+DXNO(11,J)
        XNO(12,J,IST)=XNO(12,J,IST)+DXNO(12,J)
        XNO(13,J,IST)=XNO(13,J,IST)+DXNO(13,J)
        XNO(14,J,IST)=XNO(14,J,IST)+DXNO(14,J)
        XNO(15,J,IST)=XNO(15,J,IST)+DXNO(15,J)
        XNO(16,J,IST)=XNO(16,J,IST)+DXNO(16,J)
        XNO(17,J,IST)=XNO(17,J,IST)+DXNO(17,J)
        XNO(18,J,IST)=XNO(18,J,IST)+DXNO(18,J)
        XNO(19,J,IST)=XNO(19,J,IST)+DXNO(19,J)
```

Table B-1. Continued.

```
      WQ=VOL=(J)=F(ID=1,J)
      XPT=VOLW(J)*XNO(5,J,IST)=WQ*(XNO(5,J,IST)-DXNO(5,J))=F(ID=1,J)*XIN
     *1(J)
      XOP=VOLW(J)*XNO(6,J,IST)=WQ*(XNO(6,J,IST)-DXNO(6,J))=F(ID=1,J)*XIN
     *1(J)
      XNH3=VOL=(J)*XNO(11,J,IST)=WQ*(XNO(11,J,IST)-DXNO(11,J))=F(ID=1,J)
     **XIN=NH3(INT)
      XNO3=VOL=(J)*XNO(9,J,IST)=WQ*(XNO(9,J,IST)-DXNO(9,J))=F(ID=1,J)*X
     *IN=O3(INT)
      XN=GASNET(1)+XNO3+XNH3
C*                                STEP 5.5
      IFILE=10+J
      WRITE(IFILE,113) INT,IDS,VNET(ID,J),(GASNET(KG),KG=1,4),HEGAS(ID,J
     *),XPT,XOP,XNO3,XNH3,XN
  113     FORMAT(1X,I3,1X,I3,1X,F7.3,1X,F7.3,1X,F7.3,1X,F7.4,1X,F7.4,
     *1X,F7.4,1X,F7.5,1X,F7.5,1X,F7.5,1X,F7.5,1X,F8.4)
      IF(IOPT.NE.2) GO TO 60
      WRITE(1,1000) IFILE,INT,IDS,VNET(ID,J),(GASNET(KG),KG=1,4),HEGAS(I
     *D,J),HEAQU(ID,J),XPT,XOP,XNO3,XNH3,XN
 1000 FORMAT(1H /1H,3I8,4F15.3/1H,24X,5F15.3)
   60 CONTINUE
      IFILE=22+J
      WRITE(IFILE,114) INT,IDS,(XNO(KN,J,IST),KN=1,NNUTO)
  114 FORMAT(1X,2I3,2F5.1,2F4.1,2F7.5,2F5.1,3F7.5,F5.2,F5.1,F5.3,
     *5E10.4)
   30 CONTINUE
   20 CONTINUE
C*                                STEP 6    INITIALIZE FOR THE BEGINNING OF
C*                                          THE NEXT INTERVAL AND LOOP BACK
C*                                          TO READ DAILY INPUT DATA.
C*
      DO 37 L=1,NMICRO
      J=MINO(L)
      TI(1,J)=TI(NDP1,J)
      TO(1,J)=TO(NDP1,J)
      F(1,J)=F(NDP1,J)
      VINI(1,J)=VINI(NDP1,J)
      VOGSTP(1,J)=VOGSTP(NDP1,J)
   37 CONTINUE
      P(1)=P(NDP1)
      IDUM=IST
      IST=IED
      IED=IDUM
      GO TO 5
   99 WRITE(40) IDS
      WRITE(1,602) IDS
      GO TO 97
   98 WRITE(1,511) INT, NDAYS, IDUM
  511 FORMAT(1X,"DATA INPUT ERROR, EXECUTION TERMINATED"
     *1X,"INT=",I8,8X,"NDAYS=",I8,8X,"IDUM=",A2)
   97 STOP
      DATA(Z(I),I=1,4)/28010.,32000.,44010.,16040./
      DATA(FA(I),I=1,4)/.7808,.2095,.00033,0.0/
      DATA(VOLG(I),I=1,12)/957.,982.,992.,980.,986.,962.,960.,
     *989.,990.,992.,989.,991. /
      DATA(XINI(I),I=1,12)/.008,.008,.008,.008,.008,.008,.008,.008,
     *.008,.008,.008,.008/
      DATA(XINNO3(I),I=1,12)/.078,.078,.078,.078,.078,.078,.078,
     *.078,.078,.078,.078,.078/
      DATA(XINNH3(I),I=1,12)/.004,.004,.004,.004,.004,.004,.004,
     *.004,.004,.004,.004,.004/
      END
      FUNCTION FRK(KG,TIN)
      DIMENSION X(11,22)
      T=TIN+9.0
      IT=T
      RT=IT
      FRK=((X(KG,IT+1)-X(KG,IT))*(T-RT)+X(KG,IT))*1.0E7
      RETURN
      DATA (X(1,I),I=1,21)/5.07,5.18,5.29,5.39,5.49,5.60,5.71,5.81
     *,5.91,6.01,6.10,6.20,6.29,6.39,6.48,6.57,6.67,6.75,6.84,6.93,7.02/
      DATA (X(2,I),I=1,21)/2.46,2.51,2.57,2.62,2.68,2.73,2.78,2.84,2.89
     *,2.95,3.00,3.05,3.11,3.16,3.21,3.26,3.31,3.36,3.42,3.47,3.52/
      DATA (X(3,I),I=1,21)/.0791,.0819,.0845,.0873,.0901,.0929,.0958
     *,.0987,.101,.104,.107,.111,.114,.117,.120,.124,.127,.130,.134
     *,.137,.141/
```

Table B-1. Continued.

```
      DATA (X(4,I),I=1,21)/2.26,2.32,2.38,2.44,2.50,2.56,2.62,2.68
     *,2.74,2.80,2.85,2.91,2.97,3.02,3.08,3.14,3.19,3.25,3.30,3.36,3.41/
      DATA (X(5,I),I=1,21)/.58,.60,.62,.64,.65,.68,.69,.71,.73,.75,.77
     *,.79,.81,.83,.84,.86,.88,.90,.92,.94,.96/
      END
      FUNCTION FVP(TIN)
      DIMENSION X(103)
      T=TIN*10.-199.0
      IT=T
      IF(IT.LT.1) IT=1
      FVP=X(IT)
      RETURN
      DATA (X(I),I=1,101)/17.54,17.64,17.75,17.86,17.97,18.09,18.20,
     *18.31,18.42,18.54,18.65,18.76,18.88,19.00,19.11,19.23,19.35,19.47,
     *19.59,19.71,19.83,19.95,20.07,20.19,20.32,20.44,20.56,20.69,20.82,
     *20.94,21.07,21.20,21.32,21.45,21.58,21.71,21.84,21.98,22.11,22.24,
     *22.38,22.51,22.65,22.78,22.92,23.06,23.20,23.34,23.48,23.62,23.76,
     *23.90,24.04,24.18,24.33,24.47,24.62,24.76,24.91,25.06,25.21,25.36,
     *25.51,25.66,25.81,25.96,26.12,26.27,26.43,26.58,26.74,26.92,27.06,
     *27.21,27.37,27.54,27.70,27.86,28.02,28.21,28.35,28.52,28.68,28.85,
     *29.02,29.18,29.35,29.53,29.70,29.87,30.04,30.22,30.39,30.56,30.74,
     *30.82,31.10,31.28,31.46,31.64,31.82/
      END
```

Appendix C

Sensitivity of Sediment Phosphorus Analysis

Table C-1. Sample calculation to determine the maximum potential change in sediment phosphorus concentration expected in the microcosm study based on the maximum sediment phosphorus release observed.

Microcosm sediment (surface area)	= 177 cm^2
Sediment profile increment sampled	= 2 cm
Bulk density of New Fork Lake sediment	= 1.34 g/cm^3
Total sediment weight in top profile	= 474 g
Max. potential release of phosphorus from sediment (based on New Fork Lake dark microcosm treated with S. La. Crude oil)	= 2.3 mg

Based on the above values the following calculation is used to determine the maximum change in sediment phosphorus content that could be expected.

$$2.3 \text{ mg P} \times \frac{1000 \text{ µg}}{\text{mg}} * \frac{1}{488 \text{ g sed.}} = 4.7 \text{ µg P/g sediment}$$

The range observed for multiple analyses of a single sediment sample was as high as 55 µg P/g sediment, thus the analytical precision was inadequate for the purpose of this experiment.

Note: Other nutrient analyses (NH_3-N, NO_3-N, NO_2-N) were hampered in a similar manner.

Recommendations: Sample a smaller increment of sediment to reduce total sediment weight in the critical upper zone of sediment-water exchange.

: Employ more precise sediment analyses.

Appendix D

Results of Statistical Analysis of Microcosm Parameters

Contents of this appendix were copied directly from computer data files; numbers of significant figures reported do not always signify the sensitivity of the analysis used.

Table D-1. Alkalinity ANOV and mean values.

LAKE	PARAMETER	S.V.	D.F.	M.S.E.	F
Bear	Alkalinity (mg/l as $CaCO_3$)	TREATMENT:	2	183.78	4.85
		ERROR (a):	6	37.88	
		TIME:	9	427.33	29.47*
		TMT.-TIME:	18	65.07	4.49*
		ERROR (b):	54	14.50	

INTRA-LAKE COMPARISON

	DIURNAL			DARK		
	CONTROL	S. LA. CRUDE	WYO. CRUDE	CONTROL	SLC	WC
O.T.M.	249.5(a)	252.5(a)	254.4(a)	256.0	259.4	254.8
DAY 0	243 (a)	243 (a)	246 (a)	244	249	243
DAY 10	250 (a)	246 (a)	249 (a)	257	259	259
DAY 20	270 (a)	259 (a)	266 (a)	271	272	270
DAY 30	255 (a)	257 (a)	257 (a)	255	242	242
DAY 40	261 (a)	260 (a)	258 (a)	262	260	257
DAY 50	243 (a)	246 (a)	244 (a)	251	251	242
DAY 60	252 (a)	255 (a)	257 (a)	259	264	264
DAY 70	246 (a)	252 (a)	256 (b)	259	260	258
DAY 80	239 (a)	256 (b)	258 (b)	255	263	259
DAY 90	237 (a)	249 (b)	253 (b)	247	274	254

(O.T.M. = Overall Treatment Means)

LAKE	PARAMETER	S.V.	D.F.	M.S.E.	F
New Fork	Alkalinity (mg/l as $CaCO_3$)	TREATMENT:	2	23.24	3.22
		ERROR (a):	3	7.22	
		TIME:	9	31.04	9.12*
		TMT.-TIME:	18	5.68	1.67
		ERROR (b):	27	3.41	

INTRA-LAKE COMPARISON

	DIURNAL			DARK		
	CONTROL	S. LA. CRUDE	WYO. CRUDE	CONTROL	SLC	WC
O.T.M.	20.32(a)	22.09(a)	22.28(a)	21.38	21.91	22.58
DAY 0	17.50(a)	17.50(a)	17.50(a)	17.9	17.9	17.9
DAY 10	18.70(a)	18.00(a)	18.25(a)	18.0	18.0	18.0
DAY 20	20.80(a)	20.55(a)	20.55(a)	20.8	20.8	20.8
DAY 30	22.75(a)	22.25(a)	22.50(a)	23.0	23.0	23.0
DAY 40	22.40(a)	22.45(a)	21.90(a)	22.9	23.8	22.9
DAY 50	22.90(a)	23.90(a)	24.15(a)	23.9	26.3	26.8
DAY 60	22.00(a)	24.40(a)	25.85(a)	18.8	21.3	25.1
DAY 70	19.55(a)	22.75(a)	24.15(a)	19.3	20.8	23.8
DAY 80	17.60(a)	21.40(a)	22.90(a)	28.0	23.3	23.8
DAY 90	19.00(a)	27.65(a)	25.00(a)	21.2	23.9	23.7

Table D-2. Total hardness ANOV and mean values.

LAKE	PARAMETER	S.V.	D.F.	M.S.E.	F
Bear	Total Hardness (mg/l as $CaCO_3$)	TREATMENT:	2	280.00	3.14
		ERROR (a):	6	89.11	
		TIME:	9	355.5	9.29*
		TMT.-TIME:	18	64.36	1.68
		ERROR (b):	54	38.29	

INTRA-LAKE COMPARISON

	DIURNAL			DARK		
	CONTROL	S. LA. CRUDE	WYO. CRUDE	CONTROL	SLC	WC
O.T.M.	258(a)	263(a)	264(a)	270	270	267
DAY 0	259(a)	254(a)	255(a)	262	260	258
DAY 10	259(a)	264(a)	267(a)	265	265	257
DAY 20	266(a)	271(a)	269(a)	285	273	269
DAY 30	269(a)	270(a)	268(a)	281	269	277
DAY 40	259(a)	258(a)	261(a)	266	264	269
DAY 50	273(a)	275(a)	267(a)	286	280	274
DAY 60	257(a)	259(a)	267(a)	268	270	276
DAY 70	248(a)	260(a)	261(a)	256	279	262
DAY 80	244(a)	256(a)	258(a)	273	263	258
DAY 90	249(a)	267(a)	267(a)	258	274	268

LAKE	PARAMETER	S.V.	D.F.	M.S.E.	F
New Fork	Total Hardness (mg/l as $CaCO_3$)	TREATMENT:	2	22.87	3.06
		ERROR (a):	3	7.48	
		TIME:	9	107.71	72.69*
		TMT.-TIME:	18	2.93	1.98
		ERROR (b):	27	1.48	

INTRA-LAKE COMPARISON

	DIURNAL			DARK		
	CONTROL	S. LA. CRUDE	WYO. CRUDE	CONTROL	SLC	WC
O.T.M.	28.10(a)	29.90(a)	30.00(a)	30.08	31.57	30.77
DAY 0	21.00(a)	21.00(a)	21.00(a)	20.7	20.7	20.7
DAY 10	22.95(a)	22.95(a)	22.95(a)	22.4	22.4	22.4
DAY 20	27.05(a)	29.60(a)	28.60(a)	29.6	29.6	28.6
DAY 30	29.00(a)	28.05(a)	28.05(a)	30.0	30.9	30.0
DAY 40	30.35(a)	31.30(a)	30.85(a)	31.8	33.8	29.9
DAY 50	31.00(a)	32.00(a)	33.00(a)	32.0	36.0	34.0
DAY 60	29.80(a)	32.30(a)	32.70(a)	32.3	36.4	37.4
DAY 70	31.40(a)	34.90(a)	33.95(a)	34.4	36.5	35.4
DAY 80	29.20(a)	34.20(a)	34.65(a)	33.7	34.7	34.7
DAY 90	29.20(a)	32.65(a)	34.20(a)	33.9	34.7	34.6

Table D-3. Calcium ANOV and mean values.

LAKE	PARAMETER	S.V.	D.F.	M.S.E.	F
Bear	Calcium (mg/l as $CaCO_3$)	TREATMENT:	2	131.81	1.33
		ERROR (a):	6	98.94	
		TIME:	9	921.38	5.67*
		TMT.-TIME:	18	130.48	0.80
		ERROR (b):	54	162.46	

INTRA-LAKE COMPARISON

	DIURNAL			DARK		
	CONTROL	S. LA. CRUDE	WYO. CRUDE	CONTROL	SLC	WC
O.T.M.	128.07(a)	131.50(a)	127.70(a)	137.70	123.90	138.40
DAY 0	135.33(a)	118.00(a)	120.67(a)	120	122	120
DAY 10	120.00(a)	114.67(a)	117.33(a)	120	116	116
DAY 20	128.00(a)	125.67(a)	129.67(a)	120	116	122
DAY 30	127.67(a)	126.67(a)	125.33(a)	132	122	124
DAY 40	151.67(a)	152.67(a)	159.00(a)	168	179	174
DAY 50	121.33(a)	134.00(a)	120.00(a)	152	88	132
DAY 60	119.33(a)	132.33(a)	116.67(a)	148	120	154
DAY 70	135.67(a)	134.00(a)	128.67(a)	168	128	132
DAY 80	119.67(a)	131.00(a)	124.67(a)	127	125	156
DAY 90	122.00(a)	146.00(a)	135.00(a)	122	123	154

LAKE	PARAMETER	S.V.	D.F.	M.S.E.	F
New Fork	Calcium (mg/l as $CaCO_3$)	TREATMENT:	2	7.36	7.09
		ERROR (a):	3	1.04	
		TIME:	9	39.19	80.57*
		TMT.-TIME:	18	0.82	1.69
		ERROR (b):	27	0.49	

INTRA-LAKE COMPARISON

	DIURNAL			DARK		
	CONTROL	S. LA. CRUDE	WYO. CRUDE	CONTROL	SLC	WC
O.T.M.	17.36(a)	18.31(a)	18.48(a)	18.91	18.92	19.30
DAY 0	11.20(a)	11.20(a)	11.20(a)	14.6	14.6	14.6
DAY 10	17.35(a)	18.40(a)	19.40(a)	19.4	18.4	18.4
DAY 20	18.40(a)	18.40(a)	18.40(a)	18.4	18.4	19.4
DAY 30	16.90(a)	16.40(a)	17.90(a)	18.4	16.4	17.4
DAY 40	17.20(a)	18.70(a)	18.70(a)	20.2	20.2	20.2
DAY 50	18.50(a)	19.00(a)	18.50(a)	22.0	20.0	20.0
DAY 60	18.20(a)	19.20(a)	20.70(a)	20.2	21.2	20.2
DAY 70	19.00(a)	20.50(a)	20.00(a)	18.5	20.5	22.6
DAY 80	18.40(a)	20.90(a)	19.90(a)	18.4	19.4	20.4
DAY 90	18.40(a)	20.40(a)	20.10(a)	19.0	20.1	19.8

Table D-4. Magnesium ANOV and mean values.

LAKE	PARAMETER	S.V.	D.F.	M.S.E.	F
Bear	Magnesium (mg/l as $CaCO_3$)	TREATMENT:	2	288.96	12.63*
		ERROR (a):	6	22.87	
		TIME:	9	1460.00	7.45*
		TMT.-TIME:	18	113.64	0.58
		ERROR (b):	54	195.87	

INTRA-LAKE COMPARISON

	DIURNAL			DARK		
	CONTROL	S. LA. CRUDE	WYO. CRUDE	CONTROL	SLC	WC
O.T.M.	130.31(a)	131.80(a)	136.27(b)	132.50	146.30	128.40
DAY 0	123.33(a)	136.00(a)	134.67(a)	142	138	138
DAY 10	138.73(a)	149.30(a)	149.37(a)	145	149	141
DAY 20	138.33(a)	145.33(a)	139.33(a)	165	157	147
DAY 30	141.33(a)	143.00(a)	143.00(a)	149	147	153
DAY 40	107.67(a)	105.67(a)	102.33(a)	98	85	95
DAY 50	152.00(a)	140.67(a)	146.67(a)	134	192	142
DAY 60	137.33(a)	126.33(a)	150.67(a)	120	155	122
DAY 70	112.67(a)	125.67(a)	132.00(a)	88	151	130
DAY 80	124.33(a)	124.67(a)	133.00(a)	146	138	102
DAY 90	127.33(a)	121.33(a)	131.67(a)	138	151	114

LAKE	PARAMETER	S.V.	D.F.	M.S.E.	F
New Fork	Magnesium (mg/l as $CaCO_3$)	TREATMENT:	2	4.39	1.19
		ERROR (a):	3	3.69	
		TIME:	9	43.52	29.20*
		TMT.-TIME:	18	2.49	1.67
		ERROR (b):	27	1.49	

INTRA-LAKE COMPARISON

	DIURNAL			DARK		
	CONTROL	S. LA. CRUDE	WYO. CRUDE	CONTROL	SLC	WC
O.T.M.	10.74(a)	11.58(a)	11.53(a)	10.78	12.65	11.77
DAY 0	9.80(a)	9.80(a)	9.80(a)	6.1	6.1	6.1
DAY 10	5.60(a)	4.55(a)	3.55(a)	4.0	4.0	3.0
DAY 20	8.65(a)	11.10(a)	10.20(a)	10.2	11.2	10.2
DAY 30	12.10(a)	11.65(a)	10.15(a)	12.6	14.5	11.6
DAY 40	13.15(a)	12.60(a)	12.15(a)	11.6	13.6	9.7
DAY 50	12.50(a)	13.00(a)	14.50(a)	12.0	16.0	12.0
DAY 60	11.60(a)	13.10(a)	12.10(a)	12.1	15.2	17.2
DAY 70	12.40(a)	14.40(a)	13.95(a)	11.8	16.0	16.9
DAY 80	10.80(a)	13.30(a)	14.75(a)	13.3	15.3	16.3
DAY 90	10.80(a)	12.25(a)	14.10(a)	14.1	14.6	14.7

Table D-5. pH ANOV and mean values.

LAKE	PARAMETER	S.V.	D.F.	M.S.E.	F
Bear	pH	TREATMENT:	2	0.157	8.19*
		ERROR (a)	6	0.019	
		TIME	9	0.199	60.41*
		TMT.-TIME	18	0.025	7.13*
		ERROR (b)	54	3.30×10^{-3}	

INTRA-LAKE COMPARISON

	DIURNAL			DARK		
	CONTROL	S. LA. CRUDE	WYO. CRUDE	CONTROL	SLC	WC
O.T.M.	8.24(a)	8.10(b)	8.13(b)	8.04	7.94	7.83
DAY 0	8.47(a)	8.50(a)	8.50(a)	8.5	8.5	8.5
DAY 10	8.07(a)	8.07(a)	8.10(a)	8.0	8.0	8.0
DAY 20	8.17(a)	8.07(b)	8.17(a)	7.9	8.0	8.0
DAY 30	8.00(a)	8.03(a)	8.07(a)	7.9	7.9	7.5
DAY 40	8.20(a)	8.13(a)	8.20(a)	7.9	7.9	7.6
DAY 50	8.43(a)	8.27(b)	8.33(b)	8.1	8.0	7.8
DAY 60	8.20(a)	8.00(b)	8.00(b)	8.0	7.8	7.7
DAY 70	8.27(a)	8.03(b)	8.00(b)	8.1	7.8	7.7
DAY 80	8.23(a)	7.93(b)	7.93(b)	7.9	7.7	7.7
DAY 90	8.33(a)	7.97(b)	7.97(b)	8.1	7.8	7.8

LAKE	PARAMETER	S.V.	D.F.	M.S.E.	F
New Fork	pH	TREATMENT:	2	0.188	6.49
		ERROR (a):	3	2.90×10^{-2}	
		TIME:	9	0.481	51.4*
		TMT.-TIME:	18	2.61×10^{-2}	2.79*
		ERROR (b):	27	9.37×10^{-3}	

INTRA-LAKE COMPARISON

	DIURNAL			DARK		
	CONTROL	S. LA. CRUDE	WYO. CRUDE	CONTROL	SLC	WC
O.T.M.	6.99(a)	6.81(a)	6.83(a)	6.50	6.56	6.56
DAY 0	6.90(a)	6.90(a)	6.90(a)	7.0	7.0	7.0
DAY 10	6.65(a)	6.65(a)	6.65(a)	6.6	6.6	6.7
DAY 20	7.40(a)	7.40(a)	7.45(a)	6.6	6.6	6.6
DAY 30	7.25(a)	7.10(a)	7.25(a)	6.3	6.6	6.7
DAY 40	7.10(a)	6.95(a)	7.15(a)	6.6	6.5	6.6
DAY 50	7.15(a)	6.85(b)	6.80(b)	6.5	6.8	6.5
DAY 60	6.95(a)	6.65(b)	6.60(b)	6.3	6.3	6.3
DAY 70	6.75(a)	6.45(b)	6.60(ab)	6.3	6.3	6.3
DAY 80	6.80(a)	6.50(b)	6.45(b)	6.4	6.5	6.4
DAY 90	6.90(a)	6.65(b)	6.40(c)	6.4	6.4	6.5

Table D-6. Total organic carbon ANOV and mean values.

LAKE	PARAMETER	S.V.	D.F.	M.S.E.	F
Bear	Total Organic Carbon (mg/l)	TREATMENT:	2	4.18	9.66*
		ERROR (a):	6	0.43	
		TIME:	9	8.26	12.01*
		TMT.-TIME:	18	1.31	1.90*
		ERROR (b):	54	0.69	

INTRA-LAKE COMPARISON

	DIURNAL			DARK		
	CONTROL	S. LA. CRUDE	WYO. CRUDE	CONTROL	SLC	WC
O.T.M.	2.32(a)	2.71(ab)	3.07(b)	1.75	2.84	2.86
DAY 0	1.00(a)	1.60(a)	1.37(a)	2.2	1.8	1.4
DAY 10	2.17(a)	1.43(a)	2.13(a)	1.5	1.2	1.2
DAY 20	1.50(a)	1.57(a)	1.53(a)	1.2	1.5	1.1
DAY 30	3.20(a)	2.77(a)	3.07(a)	2.6	2.3	2.0
DAY 40	2.37(a)	1.80(a)	2.63(a)	2.5	2.6	2.4
DAY 50	3.57(a)	3.27(a)	2.67(a)	1.6	3.9	3.3
DAY 60	2.10(a)	2.67(a)	3.07(a)	0.8	3.5	3.6
DAY 70	2.03(a)	3.20(ab)	3.83(b)	1.2	3.9	4.3
DAY 80	2.80(a)	4.20(ab)	4.83(b)	2.5	3.8	5.3
DAY 90	2.47(a)	4.57(b)	5.33(b)	1.4	3.9	4.0

LAKE	PARAMETER	S.V.	D.F.	M.S.E.	F
New Fork	Total Organic Carbon (mg/l)	TREATMENT:	2	7.93	13.46*
		ERROR (a):	3	0.59	
		TIME:	9	18.03	18.51*
		TMT.-TIME:	18	1.71	1.75
		ERROR (b):	27	0.97	

INTRA-LAKE COMPARISON

	DIURNAL			DARK		
	CONTROL	S. LA. CRUDE	WYO. CRUDE	CONTROL	SLC	WC
O.T.M.	2.16(a)	3.27(b)	3.22(b)	1.78	2.62	2.39
DAY 0	2.60(a)	2.60(a)	2.60(a)	1.9	1.9	1.9
DAY 10	2.15(a)	3.10(a)	2.05(a)	3.7	2.4	2.3
DAY 20	3.05(a)	2.25(a)	2.15(a)	0.5	0.5	0.5
DAY 30	1.35(a)	1.30(a)	2.20(a)	1.1	1.2	1.2
DAY 40	1.60(a)	2.00(a)	1.85(a)	0.5	0.5	0.5
DAY 50	1.00(a)	2.45(a)	2.00(a)	1.2	2.6	2.1
DAY 60	0.50(a)	2.80(b)	3.60(b)	0.5	4.4	3.9
DAY 70	0.50(a)	3.05(b)	4.45(b)	0.8	2.8	4.2
DAY 80	2.15(a)	3.90(ab)	4.50(b)	2.8	3.9	3.6
DAY 90	6.65(a)	9.25(b)	6.80(a)	4.8	5.9	3.7

Table D-7. Ammonia ANOV and mean values.

LAKE	PARAMETER	S.V.	D.F.	M.S.E.	F
Bear	Ammonia (mg/l)	TREATMENT:	2	1.0×10^{-5}	0.89
		ERROR (a):	6	2.09×10^{-5}	
		TIME:	9	2.80×10^{-3}	170.21*
		TMT.-TIME:	18	1.46×10^{-5}	0.53
		ERROR (b):	54	1.64×10^{-5}	

INTRA-LAKE COMPARISON

	DIURNAL			DARK		
	CONTROL	S. LA. CRUDE	WYO. CRUDE	CONTROL	SLC	WC
O.T.M.	0.012(a)	0.012(a)	0.011(a)	0.016	0.015	0.017
DAY 0	0.060(a)	0.057(a)	0.064(a)	0.064	0.064	0.058
DAY 10	0.011(a)	0.011(a)	0.010(a)	0.034	0.019	0.033
DAY 20	0.005(a)	0.001(a)	0.001(a)	0.007	0.003	0.002
DAY 30	0.005(a)	0.008(a)	0.005(a)	0.009	0.012	0.010
DAY 40	0.019(a)	0.013(a)	0.010(a)	0.022	0.011	0.031
DAY 50	0.002(a)	0.005(a)	0.000(a)	0.001	0.001	0.000
DAY 60	0.002(a)	0.003(a)	0.003(a)	0.004	0.009	0.004
DAY 70	0.008(a)	0.009(a)	0.007(a)	0.008	0.015	0.016
DAY 80	0.000(a)	0.000(a)	0.000(a)	0.003	0.000	0.003
DAY 90	0.009(a)	0.012(a)	0.009(a)	0.007	0.011	0.016

LAKE	PARAMETER	S.V.	D.F.	M.S.E.	F
New Fork	Ammonia (mg/l)	TREATMENT:	2	7.43×10^{-5}	0.94
		ERROR (a):	3	7.90×10^{-5}	
		TIME:	9	1.66×10^{-3}	19.01*
		TMT.-TIME:	18	2.75×10^{-5}	0.32
		ERROR (b):	27	8.71×10^{-5}	

INTRA-LAKE COMPARISON

	DIURNAL			DARK		
	CONTROL	S. LA. CRUDE	WYO. CRUDE	CONTROL	SLC	WC
O.T.M.	0.010(a)	0.014(a)	0.012(a)	0.022	0.036	0.028
DAY 0	0.049(a)	0.049(a)	0.049(a)	0.052	0.052	0.052
DAY 10	0.028(a)	0.037(a)	0.043(a)	0.070	0.062	0.040
DAY 20	0.004(a)	0.011(a)	0.003(a)	0.000	0.002	0.006
DAY 30	0.001(a)	0.008(a)	0.004(a)	0.004	0.001	0.005
DAY 40	0.002(a)	0.004(a)	0.004(a)	0.005	0.002	0.006
DAY 50	0.000(a)	0.001(a)	0.000(a)	0.000	0.002	0.000
DAY 60	0.001(a)	0.001(a)	0.003(a)	0.003	0.001	0.002
DAY 70	0.006(a)	0.006(a)	0.007(a)	0.019	0.041	0.022
DAY 80	0.006(a)	0.018(a)	0.003(a)	0.036	0.100	0.061
DAY 90	0.002(a)	0.000(a)	0.000(a)	0.033	0.100	0.089

Table D-8. Nitrite ANOV and mean values.

LAKE	PARAMETER	S.V.	D.F.	M.S.E.	F
Bear	Nitrite (mg/l)	TREATMENT:	2	1.94×10^{-6}	1.02
		ERROR (a):	6	1.90×10^{-6}	
		TIME:	9	1.68×10^{-4}	90.60*
		TMT.-TIME:	18	8.33×10^{-7}	0.45
		ERROR (b):	54	1.85×10^{-6}	

INTRA-LAKE COMPARISON

	DIURNAL			DARK		
	CONTROL	S. LA. CRUDE	WYO. CRUDE	CONTROL	SLC	WC
O.T.M.	0.003(a)	0.003(a)	0.003(a)	0.017	0.008	0.013
DAY 0	0.006(a)	0.005(a)	0.004(a)	0.003	0.004	0.002
DAY 10	0.014(a)	0.016(a)	0.014(a)	0.075	0.064	0.063
DAY 20	0.002(a)	0.002(a)	0.001(a)	0.074	0.001	0.054
DAY 30	0.001(a)	0.002(a)	0.001(a)	0.007	0.005	0.003
DAY 40	0.001(a)	0.001(a)	0.001(a)	0.001	0.001	0.001
DAY 50	0.001(a)	0.001(a)	0.001(a)	0.001	0.001	0.003
DAY 60	0.001(a)	0.001(a)	0.001(a)	0.001	0.003	0.001
DAY 70	0.001(a)	0.001(a)	0.001(a)	0.001	0.001	0.001
DAY 80	0.001(a)	0.001(a)	0.001(a)	0.001	0.001	0.001
DAY 90	0.001(a)	0.002(a)	0.001(a)	0.006	0.003	0.001

LAKE	PARAMETER	S.V.	D.F.	M.S.E.	F
New Fork	Nitrite (mg/l)	TREATMENT:	2	5.17×10^{-7}	0.76
		ERROR (a):	3	6.83×10^{-7}	
		TIME:	9	1.55×10^{-5}	31.16*
		TMT.-TIME:	18	4.43×10^{-7}	0.89
		ERROR (b):	27	4.98×10^{-7}	

INTRA-LAKE COMPARISON

	DIURNAL			DARK		
	CONTROL	S. LA. CRUDE	WYO. CRUDE	CONTROL	SLC	WC
O.T.M.	0.002(a)	0.002(a)	0.002(a)	0.003	1.002	0.002
DAY 0	0.002(a)	0.002(a)	0.002(a)	0.002	0.002	0.002
DAY 10	0.007(a)	0.006(a)	0.006(a)	0.013	0.007	0.006
DAY 20	0.001(a)	0.001(a)	0.002(a)	0.002	0.001	0.002
DAY 30	0.001(a)	0.001(a)	0.001(a)	0.001	0.001	0.001
DAY 40	0.001(a)	0.001(a)	0.001(a)	0.005	0.001	0.001
DAY 50	0.001(a)	0.001(a)	0.001(a)	0.001	0.001	0.001
DAY 60	0.001(a)	0.001(a)	0.001(a)	0.001	0.001	0.001
DAY 70	0.001(a)	0.001(a)	0.001(a)	0.001	0.001	0.001
DAY 80	0.004(a)	0.001(a)	0.001(a)	0.001	0.001	0.001
DAY 90	0.001(a)	0.001(a)	0.001(a)	0.002	0.001	0.003

Table D-9. Nitrate ANOV and mean values.

LAKE	PARAMETER	S.V.	D.F.	M.S.E.	F
Bear	Nitrate (mg/l)	TREATMENT:	2	3.94×10^{-4}	0.11
		ERROR (a):	6	1.05×10^{-2}	
		TIME:	9	4.29×10^{-2}	4.74*
		TMT.-TIME:	18	1.66×10^{-2}	0.91
		ERROR (b):	54	5.43×10^{-2}	

INTRA-LAKE COMPARISON

	DIURNAL			DARK		
	CONTROL	S. LA. CRUDE	WYO. CRUDE	CONTROL	SLC	WC
O.T.M.	0.043(a)	0.045(a)	0.040(a)	0.122	0.066	0.091
DAY 0	0.084(a)	0.119(a)	0.079(a)	0.070	0.076	0.088
DAY 10	0.056(a)	0.060(a)	0.057(a)	0.035	0.036	0.047
DAY 20	0.022(a)	0.038(a)	0.012(a)	0.106	0.139	0.246
DAY 30	0.092(a)	0.028(a)	0.025(a)	0.143	0.129	0.147
DAY 40	0.039(a)	0.022(a)	0.042(a)	0.139	0.119	0.139
DAY 50	0.009(a)	0.009(a)	0.012(a)	0.149	0.009	0.019
DAY 60	0.016(a)	0.032(a)	0.029(a)	0.139	0.017	0.029
DAY 70	0.049(a)	0.036(a)	0.029(a)	0.139	0.019	0.039
DAY 80	0.042(a)	0.042(a)	0.052(a)	0.199	0.059	0.079
DAY 90	0.029(a)	0.065(a)	0.064(a)	0.104	0.057	0.079

LAKE	PARAMETER	S.V.	D.F.	M.S.E.	F
New Fork	Nitrate (mg/l)	TREATMENT:	2	3.26×10^{-2}	1.24
		ERROR (a):	3	6.45×10^{-4}	
		TIME:	9	1.92×10^{-2}	50.47*
		TMT.-TIME:	18	1.08×10^{-2}	0.77
		ERROR (b):	27	1.55×10^{-2}	

INTRA-LAKE COMPARISON

	DIURNAL			DARK		
	CONTROL	S. LA. CRUDE	WYO. CRUDE	CONTROL	SLC	WC
O.T.M.	0.037(a)	0.035(a)	0.106(a)	0.113	0.090	0.082
DAY 0	0.100(a)	0.100(a)	0.100(a)	0.100	0.100	0.100
DAY 10	0.144(a)	0.134(a)	0.159(a)	0.127	0.153	0.154
DAY 20	0.019(a)	0.014(a)	0.044(a)	0.198	0.199	0.198
DAY 30	0.034(a)	0.014(a)	0.044(a)	0.209	0.189	0.199
DAY 40	0.024(a)	0.009(a)	0.274(a)	0.114	0.109	0.099
DAY 50	0.009(a)	0.009(a)	0.009(a)	0.079	0.009	0.009
DAY 60	0.009(a)	0.009(a)	0.029(a)	0.059	0.009	0.009
DAY 70	0.009(a)	0.009(a)	0.009(a)	0.079	0.079	0.009
DAY 80	0.007(a)	0.024(a)	0.014(a)	0.079	0.009	0.029
DAY 90	0.019(a)	0.029(a)	0.379(a)	0.088	0.039	0.017

Table D-10. Orthophosphate ANOV and mean values.

LAKE	PARAMETER	S.V.	D.F.	M.S.E.	F
Bear	Ortho-phosphate (mg/l)	TREATMENT:	2	1.08×10^{-6}	0.87
		ERROR (a):	6	1.24×10^{-6}	
		TIME:	9	7.58×10^{-5}	91.35*
		TMT.-TIME:	18	1.23×10^{-6}	1.49
		ERROR (b):	54	8.29×10^{-7}	

INTRA-LAKE COMPARISON

	DIURNAL			DARK		
	CONTROL	S. LA. CRUDE	WYO. CRUDE	CONTROL	SLC	WC
O.T.M.	0.002(a)	0.003(a)	0.002(a)	0.008	0.004	0.005
DAY 0	0.008(a)	0.011(a)	0.010(a)	0.009	0.008	0.008
DAY 10	0.004(a)	0.004(a)	0.003(a)	0.005	0.005	0.006
DAY 20	0.000(a)	0.001(a)	0.000(a)	0.006	0.005	0.006
DAY 30	0.001(a)	0.002(a)	0.002(a)	0.007	0.007	0.008
DAY 40	0.001(a)	0.001(a)	0.001(a)	0.009	0.010	0.011
DAY 50	0.002(a)	0.001(a)	0.001(a)	0.009	0.002	0.002
DAY 60	0.000(a)	0.000(a)	0.000(a)	0.007	0.001	0.000
DAY 70	0.004(a)	0.003(a)	0.003(a)	0.010	0.004	0.004
DAY 80	0.000(a)	0.000(a)	0.000(a)	0.006	0.000	0.000
DAY 90	0.003(a)	0.004(a)	0.003(a)	0.008	0.002	0.002

LAKE	PARAMETER	S.V.	D.F.	M.S.E.	F
New Fork	Ortho-phosphate (mg/l)	TREATMENT:	2	7.17×10^{-5}	19.02*
		ERROR (a):	3	3.77×10^{-6}	
		TIME:	9	2.83×10^{-4}	27.9*
		TMT.-TIME:	18	2.54×10^{-5}	2.50*
		ERROR (b):	27	1.02×10^{-5}	

INTRA-LAKE COMPARISON

	DIURNAL			DARK		
	CONTROL	S. LA. CRUDE	WYO. CRUDE	CONTROL	SLC	WC
O.T.M.	0.004(a)	0.008(b)	0.007(b)	0.008	0.049	0.037
DAY 0	0.018(a)	0.018(a)	0.018(a)	0.015	0.015	0.015
DAY 10	0.016(a)	0.018(a)	0.015(a)	0.015	0.015	0.015
DAY 20	0.001(a)	0.003(a)	0.002(a)	0.008	0.009	0.009
DAY 30	0.000(a)	0.006(a)	0.000(a)	0.013	0.013	0.012
DAY 40	0.001(a)	0.000(a)	0.001(a)	0.010	0.010	0.005
DAY 50	0.002(a)	0.002(a)	0.003(a)	0.003	0.003	0.004
DAY 60	0.001(a)	0.001(a)	0.002(a)	0.001	0.019	0.026
DAY 70	0.001(a)	0.004(ab)	0.008(b)	0.005	0.136	0.131
DAY 80	0.001(a)	0.022(b)	0.017(b)	0.005	0.228	0.153
DAY 90	0.000(a)	0.008(b)	0.003(ab)	0.002	0.044	0.001

Table D-11. Total phosphorus ANOV and mean values.

LAKE	PARAMETER	S.V.	D.F.	M.S.E.	F
Bear	Total Phos-phorus (mg/l)	TREATMENT:	2	1.36×10^{-5}	0.46
		ERROR (a):	6	2.98×10^{-5}	
		TIME:	9	5.00×10^{-4}	15.30*
		TMT.-TIME:	18	7.66×10^{-6}	0.23
		ERROR (b):	54	3.37×10^{-5}	

INTRA-LAKE COMPARISON

	DIURNAL			DARK		
	CONTROL	S. LA. CRUDE	WYO. CRUDE	CONTROL	SLC	WC
O.T.M.	0.009(a)	0.010(a)	0.010(a)	0.013	0.010	0.013
DAY 0	0.015(a)	0.013(a)	0.014(a)	0.013	0.015	0.021
DAY 10	0.009(a)	0.012(a)	0.012(a)	0.014	0.008	0.010
DAY 20	0.005(a)	0.009(a)	0.007(a)	0.009	0.008	0.010
DAY 30	0.007(a)	0.008(a)	0.008(a)	0.010	0.010	0.010
DAY 40	0.006(a)	0.007(a)	0.007(a)	0.009	0.009	0.010
DAY 50	0.005(a)	0.007(a)	0.007(a)	0.012	0.008	0.017
DAY 60	0.001(a)	0.002(a)	0.002(a)	0.008	0.006	0.004
DAY 70	0.031(a)	0.024(a)	0.029(a)	0.030	0.024	0.034
DAY 80	0.002(a)	0.004(a)	0.005(a)	0.007	0.005	0.005
DAY 90	0.011(a)	0.013(a)	0.014(a)	0.016	0.011	0.013

LAKE	PARAMETER	S.V.	D.F.	M.S.E.	F
New Fork	Total Phos-phorus (mg/l)	TREATMENT:	2	5.29×10^{-4}	2.66
		ERROR (a):	3	1.99×10^{-4}	
		TIME:	9	1.14×10^{-3}	5.23*
		TMT.-TIME:	18	2.45×10^{-4}	1.12
		ERROR (b):	27	2.18×10^{-4}	

INTRA-LAKE COMPARISON

	DIURNAL			DARK		
	CONTROL	S. LA. CRUDE	WYO. CRUDE	CONTROL	SLC	WC
O.T.M.	0.010(a)	0.019(a)	0.019(a)	0.011	0.081	0.062
DAY 0	0.032(a)	0.032(a)	0.031(a)	0.028	0.028	0.028
DAY 10	0.024(a)	0.025(a)	0.022(a)	0.018	0.020	0.021
DAY 20	0.005(a)	0.007(a)	0.006(a)	0.016	0.019	0.013
DAY 30	0.005(a)	0.004(a)	0.004(a)	0.013	0.017	0.016
DAY 40	0.001(a)	0.002(a)	0.001(a)	0.004	0.014	0.004
DAY 50	0.004(a)	0.006(a)	0.005(a)	0.012	0.011	0.013
DAY 60	0.003(a)	0.007(a)	0.014(a)	0.002	0.089	0.107
DAY 70	0.009(a)	0.011(a)	0.017(a)	0.010	0.154	0.146
DAY 80	0.021(a)	0.034(a)	0.030(a)	0.005	0.256	0.161
DAY 90	0.000(a)	0.066(a)	0.056(a)	0.002	0.204	0.109

Table D-12. Dissolved oxygen ANOV and mean values.

LAKE	PARAMETER	S.V.	D.F.	M.S.E.	F
Bear	Dissolved Oxygen (mg/l)	TREATMENT:	2	29.7	28.80*
		ERROR (a):	6	1.03	
		TIME:	9	5.14	30.36*
		TMT.-TIME:	18	4.60	27.15*
		ERROR (b):	54	0.17	

INTRA-LAKE COMPARISON

	DIURNAL			DARK		
	CONTROL	S. LA. CRUDE	WYO. CRUDE	CONTROL	SLC	WC
O.T.M.	8.06(a)	6.48(b)	6.22(b)	6.42	4.35	4.50
DAY 0	7.37(a)	7.30(a)	7.43(a)	7.4	7.3	7.6
DAY 10	7.17(a)	7.23(a)	7.17(a)	7.3	7.2	7.2
DAY 20	7.83(a)	7.60(a)	7.87(a)	6.7	6.7	6.9
DAY 30	7.73(a)	7.87(a)	7.77(a)	6.7	6.7	6.9
DAY 40	7.43(a)	7.40( )	7.63( )	6.1	6.0	6.1
DAY 50	8.10(a)	6.97(b)	6.53(b)	6.4	3.4	4.0
DAY 60	8.17(a)	5.57(b)	5.47(b)	6.0	1.9	2.2
DAY 70	8.47(a)	5.40(b)	4.97(b)	5.3	1.8	1.6
DAY 80	9.13(a)	4.70(b)	4.03(b)	6.3	1.4	1.4
DAY 90	9.17(a)	4.77(b)	3.30(b)	6.0	1.1	1.1

LAKE	PARAMETER	S.V.	D.F.	M.S.E.	F
New Fork	Dissolved Oxygen (mg/l)	TREATMENT:	2	56.39	13.12*
		ERROR (a):	3	4.30	
		TIME:	9	21.35	26.20*
		TMT.-TIME:	18	7.23	8.87*
		ERROR (b):	27	0.81	

INTRA-LAKE COMPARISON

	DIURNAL			DARK		
	CONTROL	S. LA. CRUDE	WYO. CRUDE	CONTROL	SLC	WC
O.T.M.	9.65(a)	7.11(b)	6.47(b)	4.87	3.84	3.92
DAY 0	7.2 (a)	7.2 (a)	7.2 (a)	7.2	7.2	7.2
DAY 10	7.5 (a)	7.5 (a)	7.6 (a)	7.3	7.0	7.4
DAY 20	9.4 (a)	9.4 (a)	9.4 (a)	7.0	6.8	6.9
DAY 30	10.0 (a)	9.8 (a)	9.9 (a)	6.5	6.2	6.4
DAY 40	11.0 (a)	10.5 (a)	10.5 (a)	5.2	5.4	5.3
DAY 50	10.5 (a)	7.9 (b)	7.3 (b)	4.3	3.0	2.3
DAY 60	10.3 (a)	6.7 (b)	5.6 (b)	3.6	1.0	0.7
DAY 70	10.3 (a)	5.4 (b)	4.1 (b)	2.8	1.0	0.8
DAY 80	10.0 (a)	2.6 (b)	2.1 (b)	2.8	0.4	1.0
DAY 90	10.4 (a)	4.4 (b)	1.4 (c)	2.0	0.4	1.2

Table D-13. Nitrogen gas ANOV and mean values.

LAKE	PARAMETER	S.V.	D.F.	M.S.E.	F
Bear	Nitrogen Gas (mole fraction)	TREATMENT:	2	9.72×10^{-3}	16.29*
		ERROR (a):	6	5.96×10^{-4}	
		TIME:	9	3.15×10^{-3}	38.30*
		TMT.-TIME:	18	1.87×10^{-3}	22.81*
		ERROR (b):	54	8.21×10^{-5}	

INTRA-LAKE COMPARISON

	DIURNAL			DARK		
	CONTROL	S. LA. CRUDE	WYO. CRUDE	CONTROL	SLC	WC
O.T.M.	0.78(a)	0.81(b)	0.81(b)	0.82	0.86	0.86
DAY 0	0.81(a)	0.81(a)	0.81(a)	0.81	0.81	0.81
DAY 10	0.80(a)	0.80(a)	0.80(a)	0.80	0.81	0.81
DAY 20	0.79(a)	0.79(a)	0.79(a)	0.81	0.81	0.81
DAY 30	0.78(a)	0.79(a)	0.78(a)	0.81	0.82	0.81
DAY 40	0.78(a)	0.78(a)	0.78(a)	0.82	0.82	0.82
DAY 50	0.78(a)	0.79(a)	0.78(a)	0.82	0.84	0.84
DAY 60	0.78(a)	0.81(a)	0.82(a)	0.83	0.90	0.89
DAY 70	0.77(a)	0.84(b)	0.84(b)	0.83	0.92	0.93
DAY 80	0.77(a)	0.85(b)	0.86(b)	0.83	0.92	0.95
DAY 90	0.76(a)	0.86(b)	0.89(b)	0.84	0.94	0.95

LAKE	PARAMETER	S.V.	D.F.	M.S.E.	F
New Fork	Nitrogen Gas (mole fraction)	TREATMENT:	2	1.40×10^{-2}	5.82
		ERROR (a):	3	2.40×10^{-3}	
		TIME:	8	5.82×10^{-3}	14.75*
		TMT.-TIME:	16	2.47×10^{-3}	6.27*
		ERROR (b):	24	3.94×10^{-4}	

INTRA-LAKE COMPARISON

	DIURNAL			DARK		
	CONTROL	S. LA. CRUDE	WYO. CRUDE	CONTROL	SLC	WC
O.T.M.	0.725(a)	0.766(ab)	0.778(b)	0.85	0.86	0.85
DAY 0	0.80 (a)	0.80 (a)	0.79 (a)	0.79	0.79	0.79
DAY 10	0.80 (a)	0.80 (a)	0.80 (a)	0.80	0.80	0.80
DAY 20	0.76 (a)	0.76 (a)	0.77 (a)	0.81	0.82	0.82
DAY 30	0.74 (a)	0.75 (a)	0.75 (a)	0.83	0.82	0.83
DAY 40	0.72 (a)	0.73 (a)	0.73 (a)	0.83	0.84	0.84
DAY 50	0.68 (a)	0.73 (b)	0.73 (b)	0.87	0.87	0.87
DAY 60	0.68 (a)	0.75 (b)	0.77 (b)	0.88	0.93	0.91
DAY 70	0.67 (a)	0.77 (b)	0.81 (b)	0.92	0.94	0.92
DAY 80	0.68 (a)	0.81 (b)	0.86 (c)	0.93	0.93	0.89
DAY 90						

Table D-14. Oxygen gas ANOV and mean values.

LAKE	PARAMETER	S.V.	D.F.	M.S.E.	F
Bear	Oxygen Gas (mole fraction)	TREATMENT:	2	9.64×10^{-3}	15.20*
		ERROR (a):	6	6.34×10^{-4}	
		TIME:	9	3.23×10^{-3}	40.20*
		TMT.-TIME:	18	1.89×10^{-3}	23.81*
		ERROR (b):	54	7.93×10^{-5}	

INTRA-LAKE COMPARISON

	DIURNAL			DARK		
	CONTROL	S. LA. CRUDE	WYO. CRUDE	CONTROL	SLC	WC
O.T.M.	0.217(a)	0.187(a)	0.184(a)	0.176	0.139	0.138
DAY 0	0.189(a)	0.191(a)	0.191(a)	0.19	0.19	0.19
DAY 10	0.199(a)	0.200(a)	0.198(a)	0.19	0.19	0.19
DAY 20	0.207(a)	0.208(a)	0.208(a)	0.19	0.19	0.19
DAY 30	0.212(a)	0.213(a)	0.215(a)	0.18	0.18	0.18
DAY 40	0.219(a)	0.218(a)	0.221(a)	0.18	0.18	0.18
DAY 50	0.222(a)	0.212(a)	0.214(a)	0.18	0.16	0.17
DAY 60	0.223(a)	0.185(b)	0.181(b)	0.17	0.10	0.11
DAY 70	0.229(a)	0.165(b)	0.164(b)	0.16	0.08	0.07
DAY 80	0.230(a)	0.146(b)	0.137(b)	0.16	0.07	0.05
DAY 90	0.237(a)	0.138(b)	0.114(c)	0.16	0.05	0.05

LAKE	PARAMETER	S.V.	D.F.	M.S.E.	F
New Fork	Oxygen Gas (mole fraction)	TREATMENT:	2	1.49×10^{-2}	29.97*
		ERROR (a):	3	4.78×10^{-4}	
		TIME:	8	5.23×10^{-3}	37.51*
		TMT.-TIME:	16	2.85×10^{-3}	20.45*
		ERROR (b):	24	1.40×10^{-4}	

INTRA-LAKE COMPARISON

	DIURNAL			DARK		
	CONTROL	S. LA. CRUDE	WYO. CRUDE	CONTROL	SLC	WC
O.T.M.	0.256(a)	0.213(b)	0.201(b)	0.150	0.132	0.132
DAY 0	0.207(a)	0.220(a)	0.207(a)	0.21	0.21	0.21
DAY 10	0.199(a)	0.198(a)	0.200(a)	0.20	0.20	0.20
DAY 20	0.240(a)	0.236(a)	0.235(a)	0.19	0.18	0.18
DAY 30	0.254(a)	0.247(a)	0.249(a)	0.17	0.18	0.17
DAY 40	0.268(a)	0.257(a)	0.262(a)	0.17	0.16	0.16
DAY 50	0.283(a)	0.238(b)	0.236(b)	0.13	0.12	0.12
DAY 60	0.283(a)	0.207(b)	0.184(b)	0.12	0.06	0.06
DAY 70	0.285(a)	0.172(b)	0.137(c)	0.08	0.04	0.04
DAY 80	0.284(a)	0.144(b)	0.098(c)	0.08	0.04	0.05
DAY 90						

Table D-15. Carbon dioxide ANOV and mean values.

LAKE	PARAMETER	S.V.	D.F.	M.S.E.	F
Bear	Carbon Dioxide (mole fraction)	TREATMENT:	2	9.16×10^{-6}	17.56*
		ERROR (a):	6	5.21×10^{-7}	
		TIME:	9	4.31×10^{-6}	51.46*
		TMT.-TIME:	18	1.47×10^{-6}	17.51*
		ERROR (b):	54	8.37×10^{-8}	

INTRA-LAKE COMPARISON

	DIURNAL			DARK		
	CONTROL	S. LA. CRUDE	WYO. CRUDE	CONTROL	SLC	WC
O.T.M.	0.0018(a)	0.0028(b)	0.0028(b)	0.0035	0.0048	0.0064
DAY 0	0.0017(a)	0.0018(a)	0.0020(a)	0.0017	0.0017	0.0016
DAY 10	0.0026(a)	0.0027(a)	0.0028(a)	0.0029	0.0030	0.0029
DAY 20	0.0020(a)	0.0022(a)	0.0020(a)	0.0031	0.0030	0.0031
DAY 30	0.0020(a)	0.0022(a)	0.0019(a)	0.0048	0.0029	0.0052
DAY 40	0.0021(a)	0.0021(a)	0.0018(a)	0.0061	0.0029	0.0090
DAY 50	0.0014(a)	0.0021(b)	0.0021(b)	0.0035	0.0057	0.0084
DAY 60	0.0018(a)	0.0027(b)	0.0028(b)	0.0030	0.0062	0.0080
DAY 70	0.0013(a)	0.0030(b)	0.0030(b)	0.0026	0.0068	0.0078
DAY 80	0.0017(a)	0.0043(b)	0.0046(b)	0.0035	0.0073	0.0088
DAY 90	0.0017(a)	0.0045(b)	0.0051(c)	0.0037	0.0085	0.0094

LAKE	PARAMETER	S.V.	D.F.	M.S.E.	F
New Fork	Carbon Dioxide (mole fraction)	TREATMENT:	2	2.79×10^{-4}	77.92*
		ERROR (a):	3	3.58×10^{-7}	
		TIME:	7	5.99×10^{-5}	260.7*
		TMT.-TIME:	14	6.59×10^{-6}	28.68*
		ERROR (b):	21	2.30×10^{-7}	

INTRA-LAKE COMPARISON

	DIURNAL			DARK		
	CONTROL	S. LA. CRUDE	WYO. CRUDE	CONTROL	SLC	WC
O.T.M.	0.0019(a)	0.0038(b)	0.0044(b)	0.0071	0.0082	0.0073
DAY 0	0.0013(a)	0.0012(a)	0.0011(a)	0.0010	0.0011	0.0010
DAY 10	0.0032(a)	0.0030(a)	0.0031(a)	0.0027	0.0030	0.0033
DAY 20	0.0004(a)	0.0005(a)	0.0006(a)	0.0047	0.0049	0.0048
DAY 30	0.0005(a)	0.0008(a)	0.0006(a)	0.0061	0.0062	0.0063
DAY 40	0.0007(a)	0.0010(a)	0.0009(a)	0.0068	0.0072	0.0069
DAY 50	0.0021(a)	0.0059(b)	0.0071(c)	0.0123	0.0134	0.0118
DAY 60	0.0032(a)	0.0083(b)	0.0102(c)	0.0122	0.0159	0.0135
DAY 70	0.0038(a)	0.0099(b)	0.0116(c)	0.0111	0.0136	0.0108
DAY 80	( )	( )	( )			
DAY 90	( )	( )	( )			

Table D-16. Methane ANOV and mean values.

LAKE	PARAMETER	S.V.	D.F.	M.S.E.	F
New Fork	Methane (mole fraction)	TREATMENT:	2	4.13×10^{-5}	0.059
		ERROR (a):	3	7.03×10^{-4}	
		TIME:	8	2.75×10^{-3}	23.88*
		TMT.-TIME:	16	1.81×10^{-5}	0.158
		ERROR (b):	24	1.15×10^{-4}	

INTRA-LAKE COMPARISON

	DIURNAL			DARK		
	CONTROL	S. LA. CRUDE	WYO. CRUDE	CONTROL	SLC	WC
O.T.M.	(a)	(a)	(a)	0	0.0089	0.0133
DAY 0	0 (a)	0 (a)	0 (a)	0	0	0
DAY 10	0 (a)	0 (a)	0 (a)	0	0	0
DAY 20	0 (a)	0 (a)	0 (a)	0	0	0
DAY 30	0 (a)	0 (a)	0 (a)	0	0	0
DAY 40	0.016(a)	0.016(a)	0.011(a)	0	0	0
DAY 50	0.033(a)	0.033(a)	0.027(a)	0	0.01	0.01
DAY 60	0.041(a)	0.046(a)	0.046(a)	0	0.02	0.02
DAY 70	0.042(a)	0.053(a)	0.051(a)	0	0.02	0.04
DAY 80	0.036(a)	0.047(a)	0.043(a)	0	0.03	0.05
DAY 90	( )	( )	( )			

Table D-17. Accumulative gas ANOV and mean values.

LAKE	PARAMETER	S.V.	D.F.	M.S.E.	F
Bear	Accum. Gases (ml)	TREATMENT:	2	21,359	4.97
		ERROR (a):	6	4,295	
		TIME:	8	1,420	4.57*
		TMT.-TIME:	16	2,936	9.44*
		ERROR (b):	48	311.0	

INTRA-LAKE COMPARISON

	DIURNAL			DARK		
	CONTROL	S. LA. CRUDE	WYO. CRUDE	CONTROL	SLC	WC
O.T.M.	13.97(a)	-42.27(b)	-13.23(c)	-92.28	-187.62	-180.99
DAY 0	-19.96(a)	-31.97(a)	-16.28(a)	-17.93	-41.55	-43.01
DAY 10	-16.79(a)	-31.08(a)	-3.20(a)	-16.12	-65.94	-70.33
DAY 20	-6.14(a)	-26.27(a)	-0.25(a)	-34.43	-93.62	-93.97
DAY 30	-5.28(a)	-17.23(a)	8.71(a)	-57.29	-133.37	-119.10
DAY 40	6.21(a)	-14.94(a)	14.72(a)	-89.64	-192.85	-165.16
DAY 50	24.88(a)	-24.33(b)	4.22(a)	-101.45	-229.74	-209.30
DAY 60	34.54(a)	-59.94(b)	-14.30(c)	-142.90	-270.55	-264.05
DAY 70	50.27(a)	-80.76(b)	-40.46(c)	-174.24	-311.33	-321.68
DAY 80	58.00(a)	-93.93(b)	-72.25(b)	-196.49	-349.62	-342.35
DAY 90	( )	( )	( )			

LAKE	PARAMETER	S.V.	D.F.	M.S.E.	F
New Fork	Accum. Gases (ml)	TREATMENT:	2	5,178.5	0.66
		ERROR (a):	3	7,815.3	
		TIME:	8	42,315	64.2*
		TMT.-TIME:	16	1,602.8	2.44*
		ERROR (b):	24	658.8	

INTRA-LAKE COMPARISON

	DIURNAL			DARK		
	CONTROL	S. LA. CRUDE	WYO. CRUDE	CONTROL	SLC	WC
O.T.M.	146.1(a)	171.6(a)	136.5(a)	-28.05	-69.93	-68.46
DAY 0	-36.6(a)	1.7(a)	-9.7(a)	-13.98	-28.89	-23.50
DAY 10	38.4(a)	82.1(a)	74.5(a)	-9.69	-40.93	-27.02
DAY 20	71.5(a)	131.8(a)	128.2(a)	-0.46	-54.89	-22.75
DAY 30	139.7(a)	202.4(a)	190.2(a)	-13.94	-54.54	-41.36
DAY 40	200.9(a)	238.3(a)	220.0(a)	-36.89	-46.71	-67.32
DAY 50	251.5(a)	262.4(a)	225.3(a)	-45.16	-75.90	-87.83
DAY 60	228.9(a)	223.1(ab)	171.8(b)	-59.19	-99.00	-104.93
DAY 70	227.5(a)	214.6(a)	143.2(b)	-37.55	-110.12	-117.58
DAY 80	193.0(a)	188.2(a)	112.2(b)	-35.64	-118.42	-123.89
DAY 90	( )	( )	( )			

Table D-18. Accumulative nitrogen ANOV and mean values.

LAKE	PARAMETER	S.V.	D.F.	M.S.E.	F
Bear	Accum. N_2 (mg)	TREATMENT:	2	7007	1.82
		ERROR (a):	6	2587	
		TIME:	8	347	2.71
		TMT.-TIME:	16	152	0.79
		ERROR (b):	48	191	

INTRA-LAKE COMPARISON

	DIURNAL			DARK		
	CONTROL	S. LA. CRUDE	WYO. CRUDE	CONTROL	SLC	WC
O.T.M.	-52.55(a)	-66.58(a)	-34.44(a)	5.77	-132.86	-121.57
DAY 0	-42.13(a)	-53.92(a)	-36.82(a)	-31.10	-51.54	-51.07
DAY 10	-52.83(a)	-67.06(a)	-38.98(a)	-21.35	-75.17	-76.02
DAY 20	-51.80(a)	-67.93(a)	-45.26(a)	-33.43	-91.02	-90.97
DAY 30	-60.99(a)	-70.35(a)	-45.45(a)	-51.01	-129.45	-114.90
DAY 40	-66.18(a)	-69.61(a)	-44.92(a)	-84.99	-166.55	-145.69
DAY 50	-52.37(a)	-54.99(a)	-23.62(a)	37.79	-142.25	-126.61
DAY 60	-53.16(a)	-68.98(a)	-22.59(a)	57.23	-155.44	-139.55
DAY 70	-44.82(a)	-70.22(a)	-20.68(a)	73.39	-184.87	-169.18
DAY 80	-52.66(a)	-76.14(a)	-27.69(a)	105.41	-199.48	-180.14
DAY 90	( )	( )	( )			

LAKE	PARAMETER	S.V.	D.F.	M.S.E.	F
New Fork	Accum. N_2 (mg/l)	TREATMENT:	2	40,622	2.92
		ERROR (a):	3	13,927	
		TIME:	7	10,106	15.17*
		TMT.-TIME:	14	977.3	1.47
		ERROR (b):	21	666.2	

INTRA-LAKE COMPARISON

	DIURNAL			DARK		
	CONTROL	S. LA. CRUDE	WYO. CRUDE	CONTROL	SLC	WC
O.T.M.	-12.71(a)	75.82(a)	73.24(a)	46.97	28.39	20.81
DAY 0	-51.52(a)	-13.11(a)	-18.95(a)	5.92	-10.17	-6.66
DAY 10	-20.95(a)	26.66(a)	26.01(a)	25.67	-10.21	4.93
DAY 20	-22.21(a)	42.28(a)	47.07(a)	47.24	-17.35	20.14
DAY 30	-9.87(a)	73.99(a)	71.29(a)	55.83	10.30	19.01
DAY 40	5.95(a)	98.93(a)	95.76(a)	62.69	26.46	25.76
DAY 50	24.08(a)	126.77(a)	123.86(a)	95.10	80.04	13.73
DAY 60	-6.56(a)	118.26(a)	116.50(a)	102.75	82.78	48.54
DAY 70	-20.63(a)	133.38(a)	124.45(a)	102.14	65.26	41.00
DAY 80	( )	( )	( )			
DAY 90	( )	( )	( )			

Table D-19. Accumulative oxygen ANOV and mean values.

LAKE	PARAMETER	S.V.	D.F.	M.S.E.	F
Bear	Accum. O_2 (mg)	TREATMENT:	2	48,924	10.99*
		ERROR (a):	6	4,450	
		TIME:	8	16,611	42.29*
		TMT.-TIME:	16	8,949	22.78*
		ERROR (b):	48	392.8	

INTRA-LAKE COMPARISON

	DIURNAL			DARK		
	CONTROL	S. LA. CRUDE	WYO. CRUDE	CONTROL	SLC	WC
O.T.M.	29.31(a)	-46.23(b)	-42.23(b)	-42.18	-177.15	-179.86
DAY 0	-2.37(a)	-6.83(a)	-4.08(a)	-11.01	-14.79	-15.72
DAY 10	6.88(a)	1.42(a)	10.39(a)	-19.63	-30.41	-33.96
DAY 20	15.67(a)	8.62(a)	20.42(a)	-36.58	-50.81	-51.81
DAY 30	21.42(a)	14.60(a)	28.93(a)	-57.28	-76.41	-70.82
DAY 40	27.19(a)	2.82(a)	16.10(a)	-74.36	-129.47	-115.86
DAY 50	32.40(a)	-45.07(b)	-40.54(b)	-42.41	-239.15	-226.60
DAY 60	45.05(a)	-90.55(b)	-78.71(b)	-44.61	-299.44	-308.55
DAY 70	53.30(a)	-134.85(b)	-137.30(b)	-45.84	-349.81	-377.96
DAY 80	64.26(a)	-166.24(b)	-197.36(b)	-47.94	-404.07	-417.43
DAY 90	( )	( )	( )			

LAKE	PARAMETER	S.V.	D.F.	M.S.E.	F
New Fork	Accum. O_2 (mg)	TREATMENT:	2	61,040	13.13*
		ERROR (a):	3	4,650	50.13*
		TIME:	7	19,655	
		TMT.-TIME:	14	11,046	28.17*
		ERROR (b):	21	392.1	

INTRA-LAKE COMPARISON

	DIURNAL			DARK		
	CONTROL	S. LA. CRUDE	WYO. CRUDE	CONTROL	SLC	WC
O.T.M.	162.3(a)	59.2(b)	51.8(b)	-205.42	-209.67	-174.13
DAY 0	-4.7(a)	-14.1(a)	1.2(a)	-27.36	-31.92	-27.52
DAY 10	65.5(a)	51.9(a)	67.3(a)	-59.23	-63.45	-59.63
DAY 20	103.7(a)	89.8(a)	111.3(a)	-89.93	-93.56	-89.06
DAY 30	164.9(a)	130.6(a)	150.7(a)	-148.18	-151.08	-136.63
DAY 40	217.6(a)	129.3(b)	139.6(b)	-218.34	-215.68	-195.84
DAY 50	241.7(a)	88.4(b)	62.9(b)	-313.41	-332.22	-227.64
DAY 60	253.9(a)	28.0(b)	-14.0(c)	-379.39	-393.83	-310.14
DAY 70	255.8(a)	-30.5(b)	-104.4(c)	-407.47	-395.65	-346.60
DAY 80	( )	( )	( )			
DAY 90	( )	( )	( )			

Table D-20. Accumulative carbon dioxide ANOV and mean values.

LAKE	PARAMETER	S.V.	D.F.	M.S.E.	F
Bear	Accum. CO_2 (mg)	TREATMENT:	2	6,488	7.57*
		ERROR (a):	6	856.6	311.1
		TIME:	8	18,451	
		TMT.-TIME:	16	1,346	22.70*
		ERROR (b):	48	59.3	

INTRA-LAKE COMPARISON

	DIURNAL			DARK		
	CONTROL	S. LA. CRUDE	WYO. CRUDE	CONTROL	SLC	WC
O.T.M.	53.11(a)	81.84(a)	77.57(a)	176.93	176.60	265.33
DAY 0	21.69(a)	22.46(a)	20.93(a)	30.39	32.19	32.10
DAY 10	25.51(a)	28.32(a)	22.33(a)	53.41	51.42	54.52
DAY 20	38.45(a)	41.85(a)	33.03(a)	109.02	70.03	117.83
DAY 30	50.07(a)	53.17(a)	41.88(a)	166.88	87.87	228.38
DAY 40	49.72(a)	65.02(a)	57.08(a)	157.03	162.34	277.91
DAY 50	62.72(a)	86.07(b)	81.75(b)	210.09	208.32	326.37
DAY 60	64.90(a)	108.27(b)	102.94(b)	233.99	263.42	378.00
DAY 70	77.53(a)	150.37(b)	150.34(b)	292.50	320.77	451.40
DAY 80	87.41(a)	181.04(b)	187.80(b)	339.10	393.08	521.86
DAY 90	( )	( )	( )			

LAKE	PARAMETER	S.V.	D.F.	M.S.E.	F
New Fork	Accum. CO_2 (mg)	TREATMENT:	2	26,453	49.9*
		ERROR (a):	3	5,305	
		TIME:	6	46,105	314.8*
		TMT.-TIME:	12	4,610	31.5*
		ERROR (b):	18	146.5	

INTRA-LAKE COMPARISON

	DIURNAL			DARK		
	CONTROL	S. LA. CRUDE	WYO. CRUDE	CONTROL	SLC	WC
O.T.M.	55.1(a)	116.9(b)	138.9(b)	412.99	432.70	386.34
DAY 0	40.1(a)	38.7(a)	43.9(a)	85.77	77.30	71.78
DAY 10	21.3(a)	24.8(a)	29.3(a)	177.26	168.78	163.10
DAY 20	24.0(a)	33.4(a)	34.3(a)	281.40	271.47	263.80
DAY 30	36.0(a)	65.4(b)	71.8(b)	408.37	412.07	390.61
DAY 40	63.1(a)	157.0(b)	183.8(b)	559.40	589.61	551.11
DAY 50	88.5(a)	220.6(b)	267.8(c)	649.37	703.80	607.91
DAY 60	112.5(a)	278.7(b)	341.3(c)	729.39	805.90	656.09
DAY 70	( )	( )	( )			
DAY 80	( )	( )	( )			
DAY 90	( )	( )	( )			

Table D-21. Chlorophyll ANOV and mean values.

LAKE	PARAMETER	S.V.	D.F.	M.S.E.	F
Bear	Chlorophyll	TREATMENT:	2	83,027.10	19.06*
		ERROR (a):	6	4,356.17	
		TIME:	7	322,848.5	25.52*
		TMT.-TIME:	14	14,525.78	1.15
		ERROR (b):	42	12,651.52	

INTRA-LAKE COMPARISON

	DIURNAL		
	CONTROL	S. LA. CRUDE	WYO. CRUDE
O.T.M.	158(a)	273(b)	236(b)
DAY 11	10(a)	13(a)	10(a)
DAY 17	520(a)	656(a)	698(a)
DAY 28	195(a)	279(a)	210(a)
DAY 34	118(a)	168(a)	153(a)
DAY 53	148(a)	500(b)	317(ab)
DAY 57	96(a)	367(b)	250(ab)
DAY 74	98(a)	116(a)	149(a)
DAY 86	75(a)	82(a)	103(a)
DAY 80	( )	( )	( )
DAY 90	( )	( )	( )

Appendix E

Important Dates and Visual Observations of Microcosm Experiments

Table E-1. Dates and observations of the New Fork Lake microcosm experiment.

July 16, 1981	Sediments added to each of the 12 microcosms. One liter of fresh lake water and a liter of media added.
July 17-18	Suspended sediment was allowed to settle from the microcosms. The room was kept dark.
July 19	All microcosms were filled in the morning. In the afternoon, one liter of the aqueous phase was removed from all future diurnal microcosms, the media from all microcosms mixed and 1 liter redistributed to each microcosm. The same procedure was followed for the future dark microcosms. The cross inoculation procedure was to help assure homogeneity between microcosms.
July 20	Cross inoculation was repeated as on July 19.
July 21 (day #1)	The gaseous phase of all microcosms was closed to atmosphere, lights were put on a 12 hour light-8 hour dark cycle for diurnal microcosms, 1 liter of fresh media was exchanged for a liter of aqueous phase in each microcosm (i.e. first media exchange day), and composite sample was performed on all diurnal and dark microcosms. This day was day #1 of the microcosm experiments. Media exchange was performed every other day and aqueous chemistry and gas analyses every 10 days for the next 90 days.
August 31 (day #42)	Oil treatments were initiated; 3.78 ml of oil was added to microcosms randomly chosen as oil treatments. The following define treatment assignments to microcosms Control, diurnal - 2, 4, 6 Control, dark - 12 SLC, diurnal - 1, 3, 7 SLC, dark - 10 WC, diurnal - 5, 8, 9 WC, dark - 11 The following observations were made on all microcosms: - The diurnal microcosms were similar in the amount and types of plant growth. - Filamentous algae dominated sides and column. - Small, discrete, spherical algal colonies were at water surface.

Table E-1. Continued.

- Various plants constituted the macrophytic community. Microcosm #9 was particularly high in macrophytic growth relative to other microcosms. Benthic blue green algae were higher in #8 and #9 than in other microcosms.
- All microcosms had visible small, discrete algal colonies in their water column.
- Park microcosms were clear, with no visible growth, #11 had 2 oligocheates.
- In general algal growth in diurnal microcosms was beginning to look less healthy than in the recent past. In particular, some side algae was beginning to slough off and all algae was getting a yellowish color.
- The following is a ranking of diurnal microcosms in the amount of vegetative biomass at various sites within the microcosm.

Microcosm Number	Bottom Algae	Top Algae	Side Algae	Macrophytes
1	4	2	1	3
2	1	3	1	5
3	6	2	1	2
4	5	2	1	6
5	2	2	1	6
6	3	1	1	3
7	7	2	1	4
8	9	3	1	6
9	8	3	2	1

September 15 (day #57) Iron was being released from sediments in #10 and #11, imparting a distinct red coloration to the aqueous phase.

September 18 (day #60) Microcosms 4, 7, and 8 were dismantled for detailed plant analyses. These microcosms were selected because they represented systems which had the least plant growth for their respective treatments.

September 23 (day #65) Microcosms #1 had oil particles (small and sparce) on filamentous algae throughout water column. Algae and macrophytes were yellowish in color and unhealthy in appearance.

#2 - plant growth healthy in appearance although filamentous algae was a pale shade of green. Macrophytic biomass greater than in other microcosms.

#3 - plant communities appear as they did in #1, not as much oil interspersed with filamentous algae as in #1.

Table E-1. Continued.

	#5 - plant community very unhealthy in appearance, macrophytes had disappeared and algae did not appear to be living. Sediment surface was reddish in color.
	#6 - much like #2 in terms of plant biomass and apparent health of plant communities. Macrophytic biomass second only to #2.
	#9 - filamentous algae and some macrophytes appeared to be dead. A grass-like macrophyte appeared healthy and was apparently unaffected by the oil.
	#10 - a floc had formed in water column, and the aqueous phase between floc particles was relatively clear.
	#11 - aqueous phase still very red due to soluble iron. No floc formation.
	#12 - aqueous clear and little growth apparent at any site within microcosm.
October 1 (day #73)	#1, 3, 5, 9 - aqueous phase had a slight trace of red due to soluble iron.
	#1, 3 - were similar in terms of plant biomass and condition. If anything the plant communities were looking less healthy with time. Dicotyledon macrophytes appeared much more healthy than those in #9 (#5 had no macrophytes).
	#5, 9 - plant communities devastated except for a grass-like macrophyte in #9.
	#2, 6 - plant communities looked healthy. Most of growth was at sediment surface where biomass was much greater than in #1, 3, 5, or 9. Macrophytic biomass was greater in #6 than in #2 at that time.
	#10 - less iron color in aqueous since floc had settled.
	#11 - floc had formed, settled and removed much of the iron color as in #10.
	#12 - still was clear with little apparent growth.
October 15 (day #87)	#1 - all plants, except recent growth of small algal colonies on microcosms sides, looked dead.

Table E-1. Continued.

	#2 - healthy looking, some macrophytes had grown as high as 55 percent of the microcosms height. #3 - patches of filamentous algae appeared 12 October and were growing very rapidly by 15 October (a substantial biomass had developed by that date). Other plant biomass appeared dead. #5 - iron particles had attached to all dead plant growth within microcosms. All plants appeared to be destroyed by oil. #6 - plant community healthy in appearance, macrophytes entirely dominated plant biomass at that time. #9 - some new growth in form of algal colonies had appeared on microcosms sides (like #1, 3). Motocolyledon macrophyte still appeared healthy. #10 - iron in solution still was clearing. #11 - more iron in solution than #10, but #11 was also clearing. #12 - sediment surface slightly red but aqueous phase was clear.
October 18 (day #90)	Final aqueous chemical analyses completed (equipment failure or precluded compositional gas analyses on day #80 and CO_2 analyses on day #70).
October 19-21	Microcosms were dismantled; final sediment and plant biomass analyses were performed.

Table E-2. Dates and observations of the Bear Lake microcosm experiment.

October 30 - November 4, 1981	These dates correspond to July 16-21 for operations performed on the microcosms.
November 5-6	Equipment failure delayed initiation of experiment, so microcosms were maintained in dark during these days.
November 7 (day #1)	Initial water chemical and gas analyses performed on all microcosms.
November 12 (day #6)	Teflon-lined gas collecting vessel caps were replaced.
November 25 (day #19)	No macrophytes in any microcosms. #1 - least plant biomass of all microcosms; some plant biomass was apparent on sediment surface, microcosm sides and stirring bar apparatus. #2 - #9 same as #1 but slightly more plant biomass.
December 18 (day #42)	All diurnal microcosms were similar, with moderate amounts of biomass on sediment surface, microcosms sides and stirring apparatus. No macrophytic growth within the microcosms was seen. Oil treatment was initiated; 3.78 ml of oil was added to randomly chosen microcosms. The following define treatment assignments to microcosms. Control, diurnal 2, 4, 7 Control, dark 11 SLC, diurnal 1, 4, 8 SLC, dark 10 WC, diurnal 3, 5, 9 WC, dark 12
January 21 (day #76)	The following is a ranking of diurnal microcosms in the amount of vegetative biomass at various sites within the microcosm

Microcosm Number	Bottom Algae	Top Algae	Side Algae	Macrophytes	Overall
1	10	np	8	np	8
2	8	1	1	np	1
3	4	4	3	np	3
4	9	np	np	np	9
5	7	2	2	np	4
6	1	3	7	np	2
7	2	5	6	1	5
8	6	7	4	np	7
9	5	6	5	np	6

np = none present

Table E-2. Continued.

	In general the plant biomass in oil-treated system did not look as healthy as those in control microcosms. Algae tended to be more yellow in color in oiled microcosms. #10 and #12 - aqueous phase was clear, obvious filamentous type growth at water surface and on stirring apparatus. #11 - aqueous phase was clear, no growth visible anywhere in microcosm.
February 4	Final aqueous chemical and gaseous analyses were completed.
February 5-7	Microcosms dismantled; final sediment and plant biomass analyses were performed.

Appendix F

Techniques, Computer Program and Nutrient Data for Laboratory Litter Decomposition Study

Contents of this appendix were copied directly from computer data files; numbers of significant figures reported do not always signify the sensitivity of the analysis used.

Table F-1. Methods and special equipment used for water nutrient analyses.

Analysis	Method	Source
Ammonia	Indophenol	APHA (1980)
Nitrite	Diazotization	APHA (1980)
Nitrate	Diazotization after cadmium reduction	APHA (1980)
Orthophosphorus	Ascorbic acid	APHA (1980)
Total Phosphorus	Ascorbic acid after acid persulfate digestion	APHA (1980)
Sediment and Litter Bag Material Phosphorus	Ascorbic acid after acid persulfate digestion	APHA (1980)

Table F-2. Nutrient mass balance program for plant litter decomposition microcosm experiments.

```
      FILE  10(KIND=DISK,TITLE="NUDATA",PROTECTION=SAVE,FILETYPE=7)
      FILE  20(KIND=DISK,TITLE="NUPELE",PROTECTION=SAVE,FILETYPE=7)
      FILE  30(KIND=DISK,TITLE="NURATE",PROTECTION=SAVE,FILETYPE=7)
      FILE  40(KIND=DISK,TITLE="TRY",PROTECTION=SAVE,FILETYPE=7)
      DIMENSION ZNUT(10,10),CONCNU(10,10),RELNUT(10,10),RELRAT(10,10),
     *NUSUM(10,10)
      C* ??? ???
      ZNUT(1,1)=8.0
      ZNUT(1,2)=8.0
      ZNUT(1,3)=4.0
      ZNUT(1,4)=0.0
      ZNUT(1,5)=77.6
      DO 10 I=1,12
      C*  I REPRESENTS INDIVIDUAL MICROCOSMS
       DO 20 J=2,8
      C* J REPRESENTS SUCCESSIVE SAMPLING DATES
      READ(10,/)OP,TP,NH3,NO2,NO3
       ZNUT(J,1)=OP
       ZNUT(J,2)=TP
       ZNUT(J,3)=NH3
       ZNUT(J,4)=NO2
       ZNUT(J,5)=NO3
      C* THIS LOOP ASSIGNS VALUES FOR EACH NUTRIENT ON EACH
      C*SAMPLING DATE TO MICROCOSM "I"
      20 CONTINUE
       DO 87 KL=1,7
       WRITE(40,/)ZNUT(KL,1),ZNUT(KL,2),ZNUT(KL,3),ZNUT(KL,4),ZNUT(KL,5)
       87 CONTINUE
       WRITE(40,/)"NEW COS"
      CHANGE=3
      VOL=9.35
      IF (I .GE.5)CHANGE=4.5
      IF (I .GE.5)VOL=14.024
      NDAYS=1
          DO 88 LK=1,5
          NUSUM(1,LK)=0
          88 CONTINUE
        DO 30 K=2,8
      C* K REPRESENTS SUCCESSIVE INTERVALS
         DO 40 L=1,5
      C* L REPRESENTS THE FIVE NUTRIENTS
         CONCNU(K,L)=((VOL*((ZNUT(K,L)+ZNUT(K-1,L))/2))-
     *  (CHANGE*ZNUT(1,L)))/(VOL+CHANGE)
         RELNUT(K,L)=(CONCNU(K,L)-ZNUT(K-1,L))*VOL
         RELRAT(K,L)=RELNUT(K,L)/NDAYS
        NDAYS=3
         IF(K .EQ. 3) NDAYS=4
         IF(K .GE. 4) NDAYS=7
         NUSUM(K,L)=NUSUM(K-1,L)+RELNUT(K,L)
         40 CONTINUE
       30 CONTINUE
      C* THESE LOOPS CALCULATE THE AMOUNT OF THE VARIOUS NUTRIENTS
      C* RELEASED FROM THE PLANTS DURING AN INTERVAL,CORRECTING
      C* FOR THE MEDIUM EXCHANGED.
      WRITE (30,303)
      303 FORMAT(2X,"MICROCOSM",1X,"INTERVAL",3X,"RATOP",3X,"RATTP",3X,
     *"RATNH3",3X,"RATNO2",3X,"RATNO3")
          DO 50 IJ=2,8
         WRITE(20,203)I,IJ,RELNUT(IJ,1),RELNUT(IJ,2),RELNUT(IJ,3),
     *RELNUT(IJ,4),RELNUT(IJ,5)
         203 FORMAT(7X,I2,7X,I2,1X,F9.1,1X,F9.1,1X,F9.1,1X,F9.1,2X,F9.1)
         WRITE(30,203)I,IJ,RELRAT(IJ,1),RELRAT(IJ,2),RELRAT(IJ,3),
     *RELRAT(IJ,4),RELRAT(IJ,5)
        50 CONTINUE
        WRITE(20,204)NUSUM(8,1),NUSUM(8,2),NUSUM(8,3),NUSUM(8,4),
     *    NUSUM(8,5)
        204 FORMAT(19X,F9.1,1X,F9.1,1X,F9.1,1X,F9.1,1X,F9.1)
      10 CONTINUE
      STOP
      END
```

Table F-3. Nutrient concentrations of plant litter decomposition microcosms on various dates.

NEW FORK MICROCOSM # 1

SAMPLING DATE	OP	TP	NH3	NO2	NO3
1	21.20	32.00	101.00	7.50	42.50
2	24.00	67.30	172.40	9.00	91.00
3	187.00	249.00	393.00	134.50	140.00
4	478.00	488.50	584.00	164.00	816.40
5	486.00	486.00	1.00	34.00	1408.00
6	200.40	229.90	8.50	5.00	1075.00
7	100.30	131.90	18.90	8.00	602.00

NEW FORK MICROCOSM # 2

SAMPLING DATE	OP	TP	NH3	NO2	NO3
1	20.50	31.50	55.50	7.00	54.50
2	18.80	72.90	70.10	5.00	55.00
3	190.30	270.20	367.00	18.00	82.00
4	586.50	641.80	813.70	150.00	601.00
5	374.00	571.00	9.00	4.00	216.20
6	374.90	431.70	17.20	9.00	1071.00
7	357.40	351.80	18.90	5.00	955.00

NEW FORK MICROCOSM # 3

SAMPLING DATE	OP	TP	NH3	NO2	NO3
1	20.10	35.00	100.00	6.00	34.00
2	14.00	20.30	23.40	2.00	8.00
3	98.50	103.60	5.50	2.50	12.00
4	142.70	217.60	10.70	3.00	27.20
5	124.00	150.00	34.00	3.00	17.20
6	23.60	44.70	30.80	2.00	78.00
7	44.20	75.40	49.10	15.00	145.00

NEW FORK MICROCOSM # 4

SAMPLING DATE	OP	TP	NH3	NO2	NO3
1	19.70	30.10	64.00	7.00	43.00
2	6.80	51.00	5.60	2.00	18.00
3	14.20	66.60	10.60	2.00	6.00
4	74.80	126.60	10.00	2.00	18.30
5	104.00	139.00	7.00	2.00	8.20
6	28.40	41.40	1.30	1.00	29.00
7	22.60	53.40	11.50	2.00	78.00

BEAR LAKE MICROCOSM # 1

SAMPLING DATE	OP	TP	NH3	NO2	NO3
1	5.80	6.80	9.20	1.00	29.20
2	161.90	295.80	38.20	1.00	9.20
3	386.00	457.00	27.00	2.00	28.00
4	855.00	1017.10	1389.00	14.00	66.00
5	739.90	828.60	460.90	1250.00	1000.00
6	527.70	586.80	13.50	200.00	1310.00
7	416.40	430.90	0.00	8.00	1002.00

BEAR LAKE MICROCOSM # 2

SAMPLING DATE	OP	TP	NH3	NO2	NO3
1	3.70	3.80	6.30	1.00	19.50
2	89.20	173.30	6.30	1.00	9.20
3	378.00	427.00	55.00	2.00	8.00
4	826.40	957.50	906.70	26.00	74.40
5	756.30	819.20	63.40	1275.00	1725.00
6	580.50	634.40	31.30	27.00	1070.00
7	462.30	479.00	0.00	20.00	1050.00

Table F-3. Continued.

BEAR LAKE MICROCOSM # 3

SAMPLING DATE	OP	TP	NH3	NO2	NO3
1	2.60	8.00	15.50	1.00	99.20
2	101.50	185.60	7.50	1.00	9.20
3	293.00	344.00	0.00	2.00	8.00
4	438.50	550.70	0.50	2.00	48.00
5	436.50	467.70	28.10	3.00	67.00
6	269.50	325.00	0.50	11.00	19.00
7	176.10	214.80	4.60	3.00	27.00

BEAR LAKE MICROCOSM # 4

SAMPLING DATE	OP	TP	NH3	NO2	NO3
1	3.40	8.20	8.50	1.00	49.20
2	9.10	60.80	3.20	1.00	59.20
3	245.00	294.00	0.00	2.00	8.00
4	463.90	547.40	3.30	3.00	47.00
5	456.30	486.50	7.90	3.00	67.00
6	306.40	345.80	0.00	2.00	8.00
7	222.10	241.80	0.00	1.00	9.00

BEAR LAKE MICROCOSM # 5

SAMPLING DATE	OP	TP	NH3	NO2	NO3
1	3.10	8.80	9.20	1.00	29.20
2	1.70	8.60	0.10	1.00	19.20
3	0.00	0.00	8.00	1.00	9.00
4	1.30	4.90	12.40	7.00	65.00
5	19.50	44.00	13.00	3.00	117.00
6	1.00	15.60	1.10	5.00	77.00
7	1.20	13.70	0.00	2.00	108.00

BEAR LAKE MICROCOSM # 6

SAMPLING DATE	OP	TP	NH3	NO2	NO3
1	49.20	59.90	9.20	1.00	19.20
2	20.90	32.20	1.20	1.00	9.20
3	0.00	27.00	5.00	1.00	9.00
4	34.70	41.40	24.40	2.00	68.00
5	49.20	66.00	12.10	2.00	128.00
6	53.80	66.20	12.70	4.00	76.00
7	17.50	31.70	7.20	2.00	98.00

BEAR LAKE MICROCOSM # 7

SAMPLING DATE	OP	TP	NH3	NO2	NO3
1	13.20	12.80	13.00	1.00	19.20
2	273.00	338.50	144.00	2.00	8.20
3	434.00	509.00	0.00	2.00	8.00
4	1058.40	1150.00	1261.00	11.00	59.00
5	990.40	1221.00	1334.90	93.00	257.00
6	913.10	1074.70	500.00	50.00	730.00
7	844.90	999.20	7.20	58.00	1282.00

BEAR LAKE MICROCOSM # 8

SAMPLING DATE	OP	TP	NH3	NO2	NO3
1	7.30	5.60	13.00	1.00	39.20
2	107.10	181.10	19.70	1.00	9.20
3	434.00	560.00	135.00	3.00	7.00
4	1179.50	1288.30	1366.90	12.00	68.00
5	1002.00	1243.00	1436.00	130.00	370.00
6	856.00	1099.00	500.00	50.00	1620.00
7	872.00	914.00	1.50	24.00	1616.00

Date 1 = Day 3
Date 2 = Day 7
Date 3 = Day 10
Date 4 = Day 14
Date 5 = Day 21
Date 6 = Day 28
Date 7 = Day 35

New Fork microcosm #1 = Unoiled
New Fork microcosm #2 = Unoiled
New Fork microcosm #3 = Oiled
New Fork microcosm #4 = Oiled

Bear Lake microcosm #1 = Unoiled
Bear Lake microcosm #2 = Unoiled
Bear Lake microcosm #3 = Oiled
Bear Lake microcosm #4 = Oiled
Bear Lake microcosm #5 = Unoiled/no litter
Bear Lake microcosm #6 = Unoiled/no litter
Bear Lake microcosm #7 = Oiled/no sediment
Bear Lake microcosm #8 = Oiled/no sediment

Appendix G

Curve Fitting Program Used for In-Situ Decomposition Study

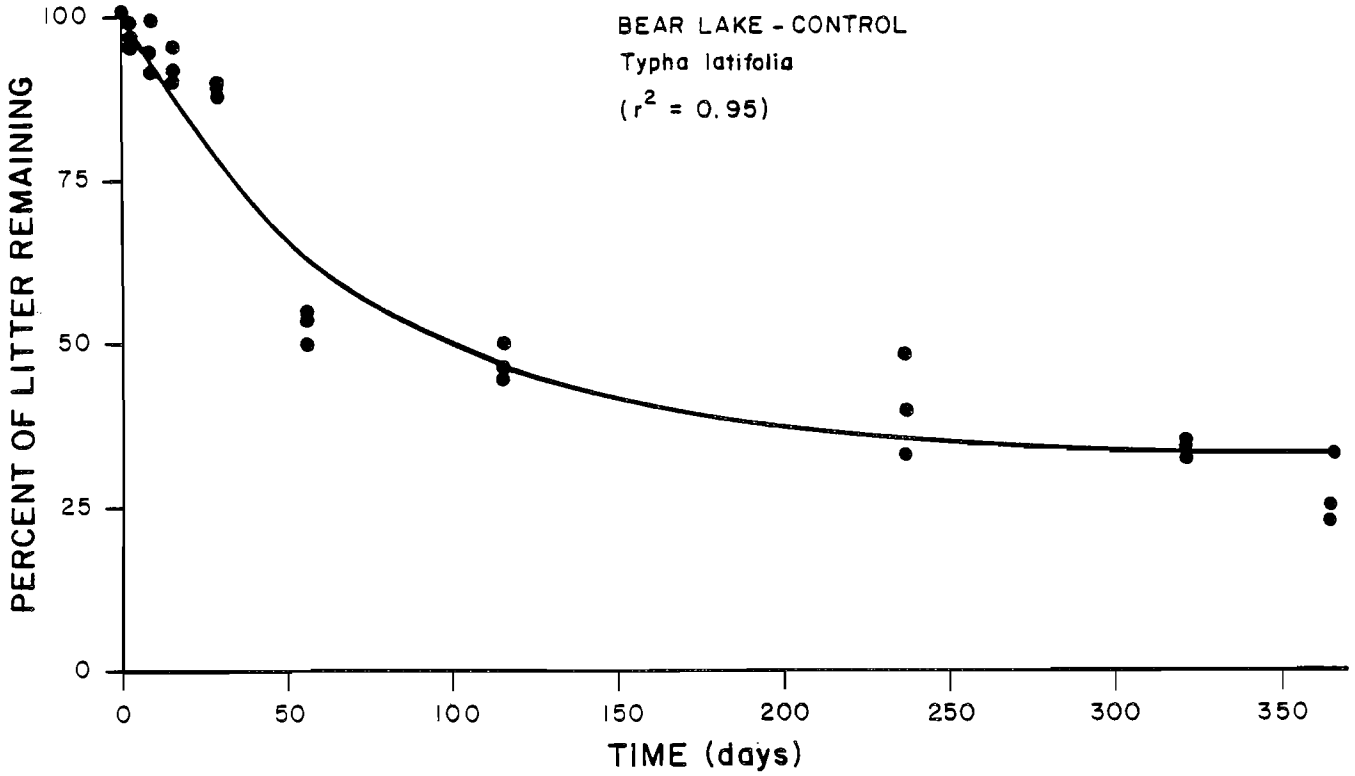

Figure G-1. Illustration of the fit of a typical set of data to the decomposition model used in this study (Equation 8).

Table G-1. Genfit, computer program to fit decomposition data to the model; $w = w_o e^{(K_o/a)(e^{-at} - 1)}$.

```
0   FILE  5=FILES,UNIT=DISK,RECORD=14,BLOCKING=30
1   FILE  6(KIND=DISK,TITLE="COEF",PROTECTION=SAVE)
2         COMMON /COEF/ NA,A(10),ADELTA(10),AMIN(10),AMAX(10),ASIGMA(10)
3         COMMON /DATUM/ NX,NPTS,X(5,100),Y(100),WT(100)
4           DIMENSION FMT(10)
5           DATA FLAMDA/0.01/
6   C*       NX  NUMBER OF INDEPENDENT VARIABLES (X,S)
7   C*       MODE WEIGHTING MODE
8   C*         -1   1/Y(I)
9   C*          0   1
10  C*          0   1/WT(I)**2
11  C*        NA NUMBER OF PARAMETERS (A,S)
12  C*    NITER MAXIMUM NUMBER OF ITERATIONS (DEFAULT 25)
13  C*    TCHI  MINIMUM CHANGE BETWEEN CHI SQUARES (DEFAULT 0.00005)
14        READ(5,10) NX,NA,MODE,NITER,TCHI,FMT
15  10    FORMAT(4I3,F8.0,10A6)
16        IF (NITER .LE. 0) NITER=25
17        IF (TCHI .EQ. 0) TCHI=0.00005
18        WRITE(6,20) NX,NA,MODE,NITER,TCHI,FMT
19  20    FORMAT('1NUMBER OF INDEPENDENT (X) VARIABLES  ',I5 /
20       *       ' NUMBER OF PARAMETERS IN THE EQUATION ',I5 /
21       *       ' MODE FOR WEIGHTING DEPENTENT VARIABLE',I5 /
22       *       ' MAXIMUM NUMBER OF ITERATIONS         ',I5 /
23       *       ' MINIMUM DIFFERENCE BETWEEN CHI SQUARE',F10.5 /
24       *       ' INPUT FORMAT = ',10A6 / '0   I      A(I)          ADELTA(I
25       *)      AMIN(I)         AMAX(I)')
26        DO 40 J=1,NA
27        READ(5,30) A(J),ADELTA(J),AMIN(J),AMAX(J)
28  30    FORMAT(4F10.0)
29        IF (ADELTA(J) .EQ. 0) ADELTA(J)=0.1*A(J) + 0.01
30        IF (AMIN(J) .IS. -0) AMIN(J)=-1.0E55
31        IF (AMAX(J) .IS. -0) AMAX(J)=1.0E55
32  40    WRITE(6,210) J,A(J),ADELTA(J),AMIN(J),AMAX(J)
33        NPTS=0
34        WRITE(6,50)
35  50    FORMAT('0RAW DATA  X(1) X(2),... Y  WT')
36  60    NPTS=NPTS + 1
37        READ(5,FMT,END=120) (X(I,NPTS),I=1,NX),Y(NPTS),WT(NPTS)
38        WRITE(6,210) NPTS,(X(I,NPTS),I=1,NX),Y(NPTS),WT(NPTS)
39  C*    CALCULATE WEIGHTS
40        IF (MODE) 90,70,80
41  70    WT(NPTS)=1.0
42        GO TO 60
43  80    WT(NPTS)=1.0/WT(NPTS)**2
44        GO TO 60
45  90    IF (Y(NPTS)) 100,70,110
46  100   WT(NPTS)=-1.0/Y(NPTS)
47        GO TO 60
48  110   WT(NPTS)=1.0/Y(NPTS)
49        GO TO 60
50  120   NPTS=NPTS - 1
51        IF (NPTS .LE. NA) STOP
52        CHI=0
53        ITER=0
54        WRITE(6,130)
55  130   FORMAT('0ITER  CHI SQ    A(1)      A(2),...')
56  C*    PARABOLIC SEARCH FIRST
57  140   ITER=ITER + 1
58        CHIS=CHI
59        CALL GRIDLS(CHI)
60        WRITE(6,150) ITER,CHI,(A(J),J=1,NA)
61  150   FORMAT(I5,11(X,G10.4))
62        CHIS=ABS(CHI - CHIS)/CHI
63        IF (CHIS .GT. 0.05) GO TO 140
64        WRITE(6,160) (ADELTA(J),J=1,NA)
65  160   FORMAT(' NEW DELTAS    ',10(X,G10.5))
66  C*    LINEAR APPROXIMATION SEARCH
67  170   ITER=ITER + 1
68        CHIS=CHI
69        CALL CURFIT(CHI,FLAMDA)
70        WRITE(6,150) ITER,CHI,(A(J),J=1,NA)
71        IF (ITER .LT. NITER .AND. ABS(CHI - CHIS) .GT. TCHI) GO TO 170
72        WRITE(6,180) (ASIGMA(J),J=1,NA)
73  180   FORMAT(' SIGMA (A)     ',10(X,G10.5))
```

Table G-1. Continued.

```
      CALL GRAPH
      STOP
210   FORMAT(I5,7(X,G14,6))
      END
C-    PARABOLIC SEARCH
      SUBROUTINE GRIDLS(CHI)
      COMMON /COEFF/ NA,A(10),ADELTA(10),AMIN(10),AMAX(10),ASTGMA(10)
      COMMON /DATUM/ NX,NPTS,X(5,100),Y(100),WT(100)
      DO 60 J=1,NA
      CHI1=0
      STEPS=0
      DO 10 I=1,NPTS
      YHAT=FUNCTN(A,X(1,I))
10    CHI1=CHI1 + WT(I)*(Y(I) - YHAT)**2
      AA=A(J)
      DELTA=ADELTA(J)
      A(J)=AA + DELTA
      CHI2=0
      DO 20 I=1,NPTS
      YHAT=FUNCTN(A,X(1,I))
20    CHI2=CHI2 + WT(I)*(Y(I) - YHAT)**2
      IF (CHI1 .GE. CHI2) GO TO 40
      A(J)=AA
      DELTA=-DELTA
      CHI3=CHI1
30    CHI1=CHI2
      CHI2=CHI3
      CHI3=0
40    STEPS=STEPS + 1
      A(J)=A(J) + DELTA
      DO 50 I=1,NPTS
      YHAT=FUNCTN(A,X(1,I))
50    CHI3=CHI3 + WT(I)*(Y(I) - YHAT)**2
      IF (CHI3 .LT. CHI2) GO TO 30
      DELTA=DELTA*(0.5 + 1.0/(1.0 + (CHI1 - CHI2)/(CHI3 - CHI2)))
      AA=A(J) - DELTA
      IF (AA .LT. AMIN(J)) AA=AMIN(J)
      IF (AA .GT. AMAX(J)) AA=AMAX(J)
      A(J)=AA
      ADELTA(J)=ADELTA(J)*STEPS/3.0
60    CONTINUE
      CHI=0
      DO 70 I=1,NPTS
      YHAT=FUNCTN(A,X(1,I))
70    CHI=CHI + WT(I)*(Y(I) - YHAT)**2
      CHI=CHI/FLOAT(NPTS - NA)
      RETURN
      END
C-    CURVE FITTING ROUTINE
      SUBROUTINE CURFIT(CHI,FLAMDA)
      COMMON /COEFF/ NA,A(10),ADELTA(10),AMIN(10),AMAX(10),ASTGMA(10)
      COMMON /DATUM/ NX,NPTS,X(5,100),Y(100),WT(100)
      DIMENSION B(10),BETA(10),DERIV(10),ALPHA(10,10),ARRAY(10,10)
      CHIS=1.0E55
      DO 10 J=1,NA
      BETA(J)=0.0
      DO 10 K=1,J
10    ALPHA(K,J)=0.0
      DO 30 I=1,NPTS
      TEMP=WT(I)*(Y(I) - FUNCTN(A,X(1,I)))
      DO 30 J=1,NA
C-    DERIVATIVES
      AA=A(J)
      DELTA=ADELTA(J)
      A1=AA + DELTA
      IF (A1 .LT. AMIN(J)) A1=AMIN(J)
      IF (A1 .GT. AMAX(J)) A1=AMAX(J)
      A(J)=A1
      YHAT=FUNCTN(A,X(1,I))
      A2=AA - DELTA
      IF (A2 .LT. AMIN(J)) A2=AMIN(J)
      IF (A2 .GT. AMAX(J)) A2=AMAX(J)
      A(J)=A2
      DERIV(J)=(YHAT - FUNCTN(A,X(1,I)))/(A1 - A2)
      BETA(J)=BETA(J) + TEMP*DERIV(J)
```

Table G-1. Continued.

```
149           DO 20 K=1,J
150     20    ALPHA(K,J)=ALPHA(K,J) + WT(I)*DERIV(J)*DERIV(K)
151     30    A(J)=AA
152     40    DO 60 J=1,NA
153           DO 50 K=1,J
154     50    ARRAY(K,J)=ALPHA(K,J)/SQRT(ALPHA(J,J)*ALPHA(K,K))
155     60    ARRAY(J,J)=1.0 + FLAMDA
156           CALL INVERT(NA,ARRAY,DET)
157           DO 90 J=1,NA
158           B(J)=A(J)
159           DO 80 K=1,NA
160           IF (J .GT. K) GO TO 70
161           AA=ARRAY(K,J)
162           GO TO 80
163     70    AA=ARRAY(J,K)
164     80    B(J)=B(J) + BETA(K)*AA/SQRT(ALPHA(J,J)*ALPHA(K,K))
165           IF (B(J) .LT. AMIN(J)) B(J)=AMIN(J)
166           IF (B(J) .GT. AMAX(J)) B(J)=AMAX(J)
167     90    CONTINUE
168           OCHI=CHIS
169           CHIS=0
170           DO 100 I=1,NPTS
171           YHAT=FUNCTN(B,X(1,I))
172     100   CHIS=CHIS + WT(I)*(Y(I) - YHAT)**2
173           CHIS=CHIS/FLOAT(NPTS - NA)
174           FLAMDA=10*FLAMDA
175           IF (CHIS .GT. OCHI) RETURN
176           IF (CHIS .GT. CHI) GO TO 40
177           DO 110 J=1,NA
178           A(J)=B(J)
179     110   ASIGMA(J)=SQRT(ARRAY(J,J)/ALPHA(J,J))
180           FLAMDA=0.01*FLAMDA
181           CHI=CHIS
182           RETURN
183           END
184     C*    SYMMETRIC MATRIX INVERSION ROUTINE
185           SUBROUTINE INVERT(N,A,DET)
186           DIMENSION A(10,10)
187           DET=1.0
188           DO 100 L=1,N
189           DET=DET * A(L,L)
190           IF (DET .EQ. 0) RETURN
191           REC=1.0/A(L,L)
192           DO 100 I=1,N
193           IF (I - L) 10,90,20
194     10    R=REC*A(I,L)
195           GO TO 30
196     20    R=REC*A(L,I)
197     30    DO 60 J=I,N
198           IF (J - L) 40,60,50
199     40    A(I,J)=A(I,J) - R*A(J,L)
200           GO TO 60
201     50    A(I,J)=A(I,J) - R*A(L,J)
202     60    CONTINUE
203           IF (I - L) 70,90,80
204     70    A(I,L)=R
205           GO TO 100
206     80    A(L,I)=R
207     90    A(L,L)=-REC
208     100   CONTINUE
209           DO 110 J=1,N
210           DO 110 I=1,J
211     110   A(I,J)=-A(I,J)
212           RETURN
213           END
214           SUBROUTINE GRAPH
215           DIMENSION YY(100),PLOT(918)
216           COMMON /COEF/ NA,A(10)
217           COMMON /DATUM/ NX,NPTS,X(5,100),Y(100)
218           NW=18
219           XLEN=50
220           WDTH=100
```

Table G-1. Continued.

```
      SYM=6HOOOPP*
      DO 10 I=1,918
10    PLOT(I)=6H
      SY=0
      YS=0
      SDIF=0
      XMIN=0
      XMAX=X(1,1)
      YMIN=0
      YMAX=Y(1)
      WRITE(6,15)
15    FORMAT('0   I  PRED. Y      OBS. Y          X...')
      DO 20 I=1,NPTS
      SY=SY + Y(I)
      YS=YS + Y(I)**2
      YY(I)=FUNCTN(A,X(1,I))
      SDIF=SDIF + (Y(I) - YY(I))**2
      XMIN=AMIN1(X(1,I),XMIN)
      XMAX=AMAX1(X(1,I),XMAX)
      YMIN=AMIN1(Y(I),YY(I),YMIN)
      YMAX=AMAX1(Y(I),YY(I),YMAX)
20    WRITE(6,30) I,YY(I),Y(I),(X(J,I),J=1,NX)
30    FORMAT(I5,7(X,G14.6))
      RS=1.0 - SDIF/(YS - SY**2/NPTS)
      WRITE(6,40) RS
40    FORMAT('0RSQ = ',F10.5)
      XSF=60TH/(XMAX - XMIN)
      YSF=XLEN/(YMAX - YMIN)
      DO 50 I=1,NPTS
      IX=(X(1,I) - XMIN) * XSF
      II=(6 - MOD(IX,6)) * 6 + 1
      J=XLEN - (Y(I) - YMIN) * YSF
      J=J * NW + IX/6 + 2
      JJ=XLEN - (YY(I) - YMIN) * YSF
      JJ=JJ * NW + IX/6 + 2
      IX=7
      IF (J .EQ. JJ) GO TO 50
      IX=23
      PLOT(J)=CONCAT(PLOT(J),SYM,II,47,8)
50    PLOT(JJ)=CONCAT(PLOT(JJ),SYM,II,IX,8)
      XMAX=XMAX + 1.0/XSF
      YMAX=YMAX + 1.0/YSF
      I=901
      YSF=5.0/YSF
      DO 60 YA=YMIN,YMAX,YSF
      PLOT(I)=YA
60    I=I - 5*NW
      WRITE(6,70) PLOT
      XSF=10.0/XSF
      WRITE(6,80) (XA,XA=XMIN,XMAX,XSF)
      RETURN
70    FORMAT(1H1,11X,10('+         '),1H+ / (F10.1,2H +,16A6,A5,1H+
     * 4(/4X,A6,2H I,16A6,A5,1H|)))
80    FORMAT(1H+,11X,10('+         '),1H+ / 5X,11F10.1)
      END
C-    FUNCTION TO BE FIT
      FUNCTION FUNCTN(A,X)
      DIMENSION A(1),X(1)
       FUNCTN=EXP((A(1)/A(2))*(EXP(-A(2)*X(1))-1))
      RETURN
      END
```

Appendix H

Temperature Correction Computer Program

Table H-1. Temp, computer program to correct plant litter decomposition rates to 20°C.

```
      FILE  A(KIND=DISK,TITLE="TEMPDA",PROTECTION=SAVE,FILETYPE=7)
      FILE  9(KIND=DISK,TITLE="DATA",PROTECTION=SAVE,FILETYPE=7)
      FILE  10(KIND=DISK,TITLE="TEMPCO",PROTECTION=SAVE,FILETYPE=7)
      DIMENSION TEMP(400)
      C* TEMPERATURE FOR EACH DATE IS READ FROM A DATAFILE
      DO 2 IJ=2,366
      READ(8,101)TEMP(IJ)
  101 FORMAT(5X,F4.1)
    2 CONTINUE
      TEMP(1)=22
      TIME=1
      READ(9,/)CKO,A,WTMIN,WTNO
      WRITE(6,/)CKO,A,WTMIN,WTNO
      WRITE(10,99)
   99 FORMAT (2X,"DAY",1X,"TEMP",3X,"CK",6X,"F",4X,"WTNO")
      WTLAST=1.0
      J=2
      IM=1
      GO TO 23
      C* THE TIME CORRESPONDING TO THE WEIGHT REMAINING IS LOCATED ON A
      C* CURVE DESCRIBING THE ACTUAL LITTER DECOMPOSITION. THIS WEIGHT AND
      C* THE WEIGHT REMAINING AT TIME PLUS ONE DAY ARE USED TO DEFINE A
      C* SIMPLE FIRST ORDER DECAY COEFFICIENT FOR THAT SINGLE DAY. THE
      C* COEFFICIENT IS THEN CORRECTED TO 20 C FROM THE TEMPERATURE OF
      C* THE LAKE ON THE DAY IN QUESTION. THE CORRECTED COEFFICIENT IS
      C* USED TO PREDICT WEIGHT LOSS DURING THE DAY IN QUESTION, IF
      C* THE LAKE'S TEMPERATURE HAD BEEN 20 C. THE LOSS DURING
      C* THE SINGLE DAY IS SUBTRACTED FROM THE WEIGHT REMAINING ON THE
      C* PREVIOUS DAY. THE TIME CORRESPONDING TO THE NEW WEIGHT REMAINING
      C* IS DETERMINED FROM ACTUAL DECOMPOSITION DATA AND SUBSEQUENT
      C* CALCULATIONS ARE MADE AS DESCRIBED ABOVE. IN THIS WAY,
      C* TEMPERATURE AND WEIGHT SPECIFIC DECAY COEFFICIENTS ARE USED
      C* TO DESCRIBE WEIGHT LOSS. THE ONLY ASSUMPTION MADE IS THAT
      C* A SIMPLE FIRST ORDER DECAY COEFFICIENT DESCRIBES WEIGHT LOSS
      C* OVER A ONE DAY PERIOD.
      DO 4 I=1,2
      IM=TIME+1
      CK=(-CKO/(A*TIME))*(EXP(-A*TIME)-1)
      F=(3.4726*EXP(0.16618*(TEMP(IM)-20)))/(1+.11*(EXP(.16618*
     *(TEMP(IM)-1))-1))
      F=1
      CK20=CK/F
      WTNO=WTLAST*EXP(-CK20)
   23 TIM=(ALOG(A*ALOG(WTNO/CKO+1))/A
      TIME=(TIME+TIM)/2
    5 CONTINUE
      WRITE(10,100)IM,TEMP(IM),CK,F,WTNO
  100 FORMAT(2X,I3,1X,F4.1,1X,F5.4,2X,F5.4,2X,F5.4)
      IF(WTNO .LT.WTMIN) GO TO 6
      TIME=TIM
      WTLAST=WTNO
    4 CONTINUE
    6 CONTINUE
      STOP
      END
```

Appendix I

Results of Statistical Analysis of Litter Decomposition Study

Contents of this appendix were copied directly from computer data files; numbers of significant figures reported do not always signify the sensitivity of the analysis used.

Table I-1. Dissolved oxygen utilization (mg/day) ANOV and mean values.

LAKE	PLANT TYPE	S.V.	D.F.	M.S.E.	F
Bear	T. latifolia	TREATMENT:	2	3.910	0.354 (ns)
		TIME:	8	263.1	23.8*
		TMT.-TIME:	16	28.95	2.62*
		ERROR:	54	11.06	

INTRA-DATE COMPARISON

	CONTROL	SOUTH LOUISIANA CRUDE	WYOMING CRUDE
O.T.M.	17.81(a)	17.18(a)	17.12(a)
DAY 3	21.7 (a)	18.3 (b)	20.3 (a)
DAY 7	16.5 (a)	17.3 (a)	19.7 (b)
DAY 14	21.5 (a)	23.3 (b)	24.8 (b)
DAY 28	32.8 (a)	24.3 (b)	22.9 (b)
DAY 55	14.8 (a)	11.4 (b)	14.2 (a)
DAY 114	8.8 (a)	13.6 (b)	10.9 (c)
DAY 236	19.3 (a)	18.2 (a)	17.7 (a)
DAY 321	6.2 (a)	15.3 (b)	10.4 (c)
DAY 365	18.7 (a)	13.0 (b)	13.3 (b)

LAKE	PLANT TYPE	S.V.	D.F.	M.S.E.	F
New Fork	P. foliosus	TREATMENT:	2	7.885	0.856 (ns)
		TIME:	8	954.9	103.7*
		TMT.-TIME:	16	19.64	2.13*
		ERROR:	54	9.210	

INTRA-DATE COMPARISON

	CONTROL	SOUTH LOUISIANA CRUDE	WYOMING CRUDE
O.T.M.	10.14(a)	11.03(a)	11.11(a)
DAY 3	26.4 (ab)	23.3 (a)	31.1 (b)
DAY 7	26.5 (a)	24.3 (a)	23.9 (a)
DAY 14	17.8 (a)	19.3 (a)	20.2 (a)
DAY 28	7.3 (a)	17.3 (b)	8.4 (a)
DAY 55	2.8 (a)	4.4 (a)	3.8 (a)
DAY 114	2.4 (a)	6.0 (a)	4.3 (a)
DAY 236	4.1 (a)	2.3 (a)	5.2 (a)
DAY 321	3.8 (a)	2.2 (a)	3.1 (a)
DAY 365	0.0 (a)	0.0 (a)	0.0 (a)

Table I-1. Continued.

LAKE	PLANT TYPE	S.V.	D.F.	M.S.E.	F
New Fork	T. latifolia	TREATMENT:	2	118.1	10.9*
		TIME:	7	259.0	23.9*
		TMT.-TIME:	14	15.44	1.43
		ERROR:	48	10.82	

	INTRA-DATE COMPARISON		
	CONTROL	SOUTH LOUISIANA CRUDE	WYOMING CRUDE
O.T.M.	16.18(a)	18.56(b)	20.61(c)
DAY 3	20.6 (a)	23.2 (a)	24.3 (a)
DAY 7	25.9 (a)	31.4 (b)	27.1 (ab)
DAY 14	19.7 (a)	17.6 (a)	22.6 (a)
DAY 28	12.5 (a)	12.0 (a)	13.8 (a)
DAY 56	15.2 (a)	19.5 (ab)	24.6 (b)
DAY 102	9.3 (a)	12.0 (ab)	15.1 (b)
DAY 314	12.8 (a)	16.0 (a)	22.2 (b)
DAY 365	13.5 (a)	16.6 (a)	15.3 (a)

LAKE	PLANT TYPE	S.V.	D.F.	M.S.E.	F
New Fork	P. foliosus	TREATMENT:	2	336.2	33.1
		TIME:	7	531.5	52.3
		TMT.-TIME:	14	23.44	2.3
		ERROR:	48	10.15	

	INTRA-DATE COMPARISON		
	CONTROL	SOUTH LOUISIANA CRUDE	WYOMING CRUDE
O.T.M.	10.27(a)	16.33(b)	17.11(b)
DAY 3	20.3 (a)	22.5 (a)	24.3 (a)
DAY 7	26.9 (a)	31.8 (a)	29.9 (a)
DAY 14	13.8 (a)	19.3 (b)	15.8 (ab)
DAY 28	6.6 (a)	8.9 (a)	16.1 (b)
DAY 56	3.4 (a)	12.6 (b)	12.6 (b)
DAY 102	3.6 (a)	9.3 (b)	10.4 (b)
DAY 314	2.8 (a)	11.3 (b)	17.9 (c)
DAY 365	4.7 (a)	14.9 (b)	9.9 (b)

Table I-2. Percent plant litter remaining ANOV and mean values.

LAKE	PLANT TYPE	S.V.	D.F.	M.S.E.	F
Bear	T. latifolia	TREATMENT:	2	94.18	3.93*
		TIME:	8	5368	224.*
		TMT.-TIME:	16	119.9	5.00*
		ERROR:	54	23.97	

	INTRA-DATE COMPARISON		
	CONTROL	SOUTH LOUISIANA CRUDE	WYOMING CRUDE
O.T.M.	63.90(a)	67.63(b)	65.66(ab)
DAY 3	97 (a)	105 (b)	92 (a)
DAY 7	95 (ab)	97 (b)	89 (b)
DAY 14	93 (a)	91 (a)	88 (a)
DAY 28	88 (a)	76 (b)	68 (c)
DAY 55	53 (a)	57 (a)	58 (a)
DAY 114	47 (a)	56 (b)	54 (ab)
DAY 236	41 (a)	50 (b)	49 (b)
DAY 321	35 (a)	40 (a)	52 (b)
DAY 365	27 (a)	36 (b)	41 (b)

LAKE	PLANT TYPE	S.V.	D.F.	M.S.E.	F
Bear	P. foliosus	TREATMENT:	2	1069	10.78*
		TIME:	8	9304	93.79*
		TMT.-TIME:	16	181.9	1.83*
		ERROR:	54	99.20	

	INTRA-DATE COMPARISON		
	CONTROL	SOUTH LOUISIANA CRUDE	WYOMING CRUDE
O.T.M.	25.1(a)	37.1(b)	34.5(b)
DAY 3	81 (ab)	78 (a)	96 (b)
DAY 7	60 (a)	81 (b)	81 (b)
DAY 14	52 (a)	62 (a)	57 (a)
DAY 28	15 (a)	30 (a)	29 (a)
DAY 55	11 (a)	31 (b)	20 (ab)
DAY 114	5 (a)	45 (b)	22 (c)
DAY 236	1 (a)	5 (a)	3 (a)
DAY 321	0 (a)	1 (a)	3 (a)
DAY 365	0 (a)	0 (a)	0 (a)

Table I-2. Continued.

LAKE	PLANT TYPE	S.V.	D.F.	M.S.E.	F
New Fork	T. latifolia	TREATMENT:	2	209.6	7.8*
		TIME:	8	1927	71.9*
		TMT.-TIME:	16	68.47	2.6*
		ERROR:	54	26.82	

	INTRA-DATE COMPARISON		
	CONTROL	SOUTH LOUISIANA CRUDE	WYOMING CRUDE
O.T.M.	81.8(a)	84.9(b)	79.4(a)
DAY 3	96 (a)	104 (a)	98 (a)
DAY 7	96 (a)	99 (a)	93 (a)
DAY 14	97 (a)	97 (a)	91 (a)
DAY 28	96 (a)	91 (ab)	86 (b)
DAY 56	92 (a)	84 (b)	76 (b)
DAY 102	81 (a)	78 (a)	74 (a)
DAY 267	68 (a)	71 (a)	69 (a)
DAY 314	58 (a)	74 (b)	67 (ab)
DAY 365	52 (a)	66 (b)	60 (b)

LAKE	PLANT TYPE	S.V.	D.F.	M.S.E.	F
New Fork	P. foliosus	TREATMENT:	2	7008	113.8*
		TIME:	8	3374	54.8
		TMT.-TIME:	16	219.0	3.56*
		ERROR:	54	61.56	

	INTRA-DATE COMPARISON		
	CONTROL	SOUTH LOUISIANA CRUDE	WYOMING CRUDE
O.T.M.	23.3(a)	50.6(b)	51.7(b)
DAY 3	61 (a)	85 (b)	77 (b)
DAY 7	55 (a)	58 (a)	63 (a)
DAY 14	49 (a)	66 (b)	67 (b)
DAY 28	24 (a)	61 (b)	54 (b)
DAY 56	7 (a)	54 (b)	51 (b)
DAY 102	7 (a)	40 (b)	59 (c)
DAY 267	3 (a)	40 (b)	35 (b)
DAY 314	0 (a)	25 (b)	27 (b)
DAY 365	4 (a)	27 (b)	33 (b)

Table I-3. Percent oil remaining ANOV and mean values.

Source of Variation	D.F.	M.S.E.	F
Lakes	1	4.171	67.6*
Plant Species	1	5.038	81.7*
Oil Types	1	0.763	12.4*
Time	7	1.394	22.6*
Lakes--Pl. Species	1	2.975	48.2*
Lakes--Oil Types	1	0.713	11.6*
Pl. Species--Oil Types	1	0.181	2.94 (ns)
Lakes--Time	7	0.358	5.80*
Pl. Species--Time	7	0.192	3.12*
Oil Types--Time	7	5.62×10^{-2}	0.91 (ns)
Lake--Pl. Species--Oil Types	1	1.251	20.3*
Lake--Pl. Species--Time	7	0.360	5.84*
Lake--Oil Type--Time	7	6.45×10^{-2}	1.05 (ns)
Pl. Species--Oil Type--Time	7	0.114	1.85 (ns)
Lake--Plant Species--Oil Types--Time	7	6.57×10^{-2}	1.07 (ns)
Error	128	6.17×10^{-2}	

Appendix J

C:N and C:P Ratio as a Function of the Proportion of Plant Litter Remaining

Table J-1. Carbon to nitrogen and carbon to phosphorus ratios for decomposing plant litter at various stages of decomposition.

Control			SLC			WC		
Prop. Rem.	C:N	C:P	Prop. Rem.	C:N	C:P	Prop. Rem.	C:N	C:P
T. latifolia (Bear Lake)								
0.95	18.8	226	0.96	19.6	226	0.93	17.3	192
0.92	25.6	172	1.01	24.2	205	0.83	21.3	286
0.92	23.0	191	0.95	22.2	206	0.92	20.5	199
0.89	16.4	177	0.91	22.3	194	0.90	21.0	248
0.89	24.0	213	0.91	18.7	241	0.89	16.6	311
0.87	29.7	144	0.92	18.6	227	0.86	24.9	340
0.55	21.5	124	0.72	18.0	368	0.66	26.5	542
0.54	33.5	166	0.76	28.1	382	0.62	20.5	834
0.50	23.2	220	0.82	28.2	247	0.76	23.0	461
0.47	26.2	196	0.54	39.4	462	0.55	28.1	464
0.47	29.9	312	0.61	36.0	433	0.64	33.4	422
0.46	34.3	403	0.54	32.3	352	0.55	28.8	518
0.36	25.9	308	0.57	25.1	255	0.54	34.1	461
0.33	28.6	298	0.40	31.5	308	0.57	23.2	500
0.35	31.1	239	0.54	30.6	160	0.51	25.1	480
0.23	17.8	299	0.42	23.5	194	0.47	32.0	296
0.26	26.5	198	0.35	21.4	322	0.48	22.3	330
0.34	21.0	238	0.42	22.9	307	0.52	25.8	493
						0.58	22.5	599
						0.56	17.6	177
						0.42	23.0	488
P. foliosus (Bear Lake)								
0.57	8.5	59	0.90	6.2	79	0.80	8.0	79
0.48	11.3	107	0.72	6.1	46	0.86	8.3	87
0.50	9.1	95	0.82	6.3	66	0.76	5.6	44
0.12	10.6	100	0.53	6.2	95	0.76	6.4	78
0.21	8.1	113	0.68	7.3	101	0.33	6.2	105
0.13	6.7	84	0.65	8.6	55	0.61	6.3	076
0.20	9.4	100	0.52	2.3	51	0.33	3.7	081
0.06	8.4	146	0.24	6.7	180	0.28	3.2	075
0.06	7.6	150	0.16	5.4	217	0.27	3.0	161
0.02	5.0	30	0.30	7.7	49	0.23	6.2	046
0.01	4.5	23	0.31	6.8	44	0.26	5.0	036
0.13	3.5	30	0.31	4.9	34	0.12	5.6	037
			0.08	4.1	14	0.25	3.9	024
						0.16	4.8	023
						0.24	6.1	023

Table J-1. Continued.

Control			SLC			WC		
Prop. Rem.	C:N	C:P	Prop. Rem.	C:N	C:P	Prop. Rem.	C:N	C:P
T. latifolia (New Fork Lake)								
0.98	33.1	289	0.98	20.7	223	0.92	24.2	188
0.93	23.0	249	0.98	22.5	337	0.95	23.0	249
0.97	33.3	253	1.02	21.3	202	0.93	26.4	232
0.98	26.2	276	1.01	27.0	273	0.82	24.4	155
0.94	21.4	259	0.97	20.1	237	0.92	22.1	215
1.00	19.7	203	0.95	19.5	240	1.00	23.0	249
0.99	29.4	298	0.94	23.3	183	0.86	26.5	242
0.91	30.0	363	0.84	21.1	245	0.93	20.9	412
0.97	26.8	291	0.94	25.8	278	0.80	24.2	290
0.95	33.0	222	0.87	21.7	254	0.77	26.4	364
0.93	27.0	185	0.82	30.3	191	0.75	28.3	324
0.90	24.0	113	0.81	26.8	210	0.77	32.2	321
0.78	37.0	180	0.80	30.0	195	0.78	33.3	396
0.85	29.0	184	0.71	26.8	354	0.74	30.4	364
0.80	35.0	172	0.84	30.5	252	0.71	25.4	353
0.72	29.0	715	0.73	39.0	999	0.72	33.4	999
0.65	38.7	802	0.61	30.6	999	0.68	34.7	999
0.66	24.9	708	0.78	31.7	991	0.67	29.1	999
0.54	27.6	193	0.68	27.6	827	0.62	27.0	405
0.67	22.9	318	0.71	27.1	440	0.65	28.1	657
0.54	26.2	271	0.80	29.8	453	0.73	27.8	578
0.54	33.6	335	0.68	38.9	707	0.62	28.9	534
0.67	23.3	241	0.72	32.2	599	0.65	36.7	652
0.54	27.7	378	0.81	39.3	759	0.73	31.0	635

Table J-1. Continued.

Control			SLC			WC		
Prop. Rem.	C:N	C:P	Prop. Rem.	C:N	C:P	Prop. Rem.	C:N	C:P
P. foliosus (New Fork Lake)								
0.51	7.9	140	0.53	7.2	122	0.58	8.1	124
0.55	5.0	37	0.52	7.5	90	0.68	8.0	116
0.59	8.3	97	0.68	8.1	145	0.62	7.6	107
0.46	5.8	74	0.68	5.7	107	0.66	7.1	121
0.47	5.7	73	0.67	8.2	159	0.67	6.8	122
0.50	5.5	70	0.65	7.0	64	0.66	7.9	146
0.18	6.0	101	0.60	5.6	69	0.70	8.6	181
0.28	5.7	119	0.54	6.8	175	0.41	6.5	133
0.26	5.3	61	0.70	7.5	150	0.51	5.4	88
0.11	7.2	114	0.52	4.2	71	0.46	6.0	103
0.20	4.3	51	0.59	4.5	52	0.53	5.5	70
0.02	6.6	181	0.52	7.1	94	0.53	5.1	83
			0.40	5.0	72	0.54	5.5	87
			0.43	5.6	81	0.48	5.0	66
			0.36	5.6	56	0.77	5.2	66
			0.41	5.4	200	0.34	1.6	228
			0.44	4.9	182	0.30	5.8	208
			0.36	5.8	247	0.43	5.4	245
			0.24	4.7	68	0.26	4.6	64
			0.30	5.0	84	0.25	4.5	69
			0.21	5.0	81	0.31	4.7	65
			0.30	5.0	82	0.26	5.3	92
			0.21	5.6	89	0.25	4.6	70
						0.31	5.2	86

Appendix K

Chemical, Gas Composition and Temperature Data of Microcosm Studies

Contents of this appendix were copied directly from computer data files; numbers of significant figures reported do not always signify the sensitivity of the analysis used.

Table K-1. Chemical and gas composition data from New Fork Lake microcosm experiment.

NEW FORK LAKE MICROCOSM # 1

DAY	ALK	HARD	PH	DO	TP	OP	CA	MG	NO3	NO2	NH3	TOC	N2	O2	CO2	CH4
0	17.50	21.00	6.94	7.20	0.0315	0.0183	11.20	9.80	0.1000	0.0020	0.0485	2.60	0.8081	0.2330	0.0011	0.0000
10	18.00	23.50	6.60	7.21	0.0220	0.0170	18.40	5.10	0.1350	0.0050	0.0210	1.60	0.8024	0.1976	0.0030	0.0000
20	21.30	28.60	7.41	9.20	0.0074	0.0039	18.40	10.20	0.0190	0.0010	0.0091	1.70	0.7695	0.2305	0.0006	0.0000
30	22.00	29.00	7.04	9.60	0.0033	0.0000	16.40	12.60	0.0190	0.0010	0.0061	1.30	0.7542	0.2413	0.0010	0.0000
40	22.50	30.80	6.92	10.30	0.0010	0.0000	18.20	12.60	0.0090	0.0010	0.0033	2.10	0.7321	0.2515	0.0012	0.0147
50	23.40	32.00	6.80	7.30	0.0059	0.0017	18.00	14.00	0.0090	0.0010	0.0022	3.10	0.7419	0.2277	0.0060	0.0294
60	24.60	32.30	6.61	6.25	0.0080	0.0018	20.20	12.10	0.0090	0.0010	0.0016	3.90	0.7662	0.1950	0.0075	0.0386
70	21.30	34.40	6.44	4.90	0.0147	0.0050	20.50	13.90	0.0090	0.0010	0.0063	3.00	0.7923	0.1608	0.0092	0.0453
80	19.50	34.70	6.46	1.57	0.0310	0.0196	20.40	14.30	0.0090	0.0010	0.0293	4.10	0.8121	0.1451		0.0409
90	33.60	34.70	6.45	1.25	0.0765	0.0030	20.30	14.40	0.0290	0.0010	0.0000	8.57				

Table K-1. Continued.

NEW FORK LAKE MICROCOSM # 2

DAY	ALK	HARD	PH	DO	TP	OP	CA	MG	NO3	NO2	NH3	TOC	N2	O2	CO2	CH4
0	17.50	21.00	6.94	7.20	0.0315	0.0183	11.20	9.80	0.1000	0.0020	0.0485	2.60	0.7989	0.2099	0.0013	0.0000
10	18.90	22.40	6.70	7.61	0.0250	0.0160	16.30	6.10	0.1340	0.0060	0.0180	1.60	0.6031	0.1969	0.0033	0.0000
20	20.80	26.50	7.41	9.20	0.0049	0.0014	18.40	8.10	0.0090	0.0010	0.0036	3.50	0.7598	0.2397	0.0003	0.0000
30	22.50	29.00	7.15	9.95	0.0051	0.0000	17.40	11.60	0.0090	0.0010	0.0005	1.20	0.7391	0.2546	0.0005	0.0000
40	21.40	29.90	6.96	10.70	0.0000	0.0000	16.20	13.70	0.0390	0.0010	0.0033	1.70	0.7074	0.2725	0.0006	0.0191
50	22.40	30.00	7.20	10.90	0.0036	0.0014	18.00	12.00	0.0090	0.0010	0.0000	1.10	0.6772	0.2867	0.0016	0.0351
60	21.30	30.30	7.05	10.60	0.0030	0.0013	19.20	11.10	0.0090	0.0010	0.0002	0.50	0.6631	0.2921	0.0024	0.0445
70	18.80	30.40	6.84	11.10	0.0050	0.0013	18.50	11.90	0.0090	0.0010	0.0055	0.50	0.6524	0.3001	0.0029	0.0458
80	17.60	28.70	6.87	10.98	0.0171	0.0009	18.40	10.30	0.0090	0.0010	0.0084	1.70	0.6457	0.3093		0.0429
90	18.70	28.90	6.85	10.90	0.0000	0.0000	18.50	10.40	0.0190	0.0010	0.0000	8.92				

NEW FORK LAKE MICROCOSM # 3

DAY	ALK	HARD	PH	DO	TP	OP	CA	MG	NO3	NO2	NH3	TOC	N2	O2	CO2	CH4
0	17.50	21.00	6.94	7.20	0.0315	0.0183	11.20	9.80	0.1000	0.0020	0.0485	2.60	0.7863	0.2067	0.0013	0.0000
10	18.00	22.40	6.70	7.66	0.0280	0.0180	18.40	4.00	0.1330	0.0070	0.0530	4.60	0.6014	0.1986	0.0029	0.0000
20	19.80	30.60	7.43	9.50	0.0061	0.0027	18.40	12.00	0.0090	0.0010	0.0130	2.80	0.7581	0.2408	0.0003	0.0000
30	22.50	27.10	7.23	9.95	0.0045	0.0006	16.40	10.70	0.0090	0.0010	0.0101	1.30	0.7376	0.2529	0.0005	0.0000
40	22.40	31.80	7.02	10.50	0.0038	0.0000	19.20	12.60	0.0090	0.0010	0.0049	1.90	0.7192	0.2629	0.0007	0.0170
50	24.40	32.00	6.90	8.40	0.0053	0.0022	20.00	12.00	0.0090	0.0010	0.0000	1.80	0.7131	0.2492	0.0058	0.0366
60	24.20	32.30	6.72	6.95	0.0052	0.0010	18.20	14.10	0.0090	0.0010	0.0009	1.70	0.7273	0.2184	0.0090	0.0540
70	24.20	35.40	6.53	5.80	0.0074	0.0025	20.50	14.90	0.0090	0.0010	0.0055	3.10	0.7553	0.1827	0.0105	0.0604
80	23.30	33.70	6.54	3.58	0.0367	0.0239	21.40	12.30	0.0390	0.0010	0.0067	3.70	0.8030	0.1421		0.0532
90	21.70	30.60	6.80	7.35	0.0557	0.0128	20.50	10.10	0.0290	0.0010	0.0000	11.29				

Table K-1. Continued.

NEW FORK LAKE MICROCOSM # 5

DAY	ALK	HARD	PH	DO	TP	OP	CA	MG	NO3	NO2	NH3	TOC	N2	O2	CO2	CH4
0	17.50	21.00	6.94	7.20	0.0315	0.0183	11.20	9.80	0.1000	0.0020	0.0485	2.60	0.7904	0.2074	0.0011	0.0000
10	18.50	23.50	6.70	7.74	0.0180	0.0130	19.40	4.10	0.1440	0.0060	0.0710	1.50	0.7993	0.2007	0.0032	0.0000
20	21.30	28.60	7.39	9.40	0.0036	0.0005	18.40	10.20	0.0690	0.0010	0.0051	2.70	0.7673	0.2327	0.0008	0.0000
30	23.50	29.00	7.21	9.75	0.0051	0.0000	18.40	10.60	0.0590	0.0010	0.0021	3.00	0.7491	0.2458	0.0008	0.0000
40	22.40	31.80	7.09	10.50	0.0010	0.0000	19.20	12.60	0.5390	0.0010	0.0057	2.10	0.7239	0.2591	0.0007	0.0160
50	24.90	32.00	6.90	7.65	0.0021	0.0028	19.00	13.00	0.0090	0.0010	0.0000	1.90	0.7172	0.2406	0.0067	0.0386
60	27.10	34.10	6.67	6.60	0.0108	0.0016	21.20	13.10	0.0090	0.0010	0.0045	4.60	0.7366	0.1977	0.0102	0.0646
70	25.00	36.50	6.84	4.80	0.0147	0.0050	20.50	16.00	0.0090	0.0010	0.0071	4.00	0.7739	0.1514	0.0115	0.0732
80	24.80	36.60	6.47	2.75	0.0372	0.0261	20.40	16.20	0.0190	0.0010	0.0040	4.30	0.8039	0.1157		0.0777
90	26.00	36.50	6.40	0.75	0.1100	0.0057	20.60	15.90	0.0090	0.0010	0.0002	7.77				

NEW FORK LAKE MICROCOSM # 6

DAY	ALK	HARD	PH	DO	TP	OP	CA	MG	NO3	NO2	NH3	TOC	N2	O2	CO2	CH4
0	17.50	21.00	6.94	7.20	0.0315	0.0183	11.20	9.80	0.1000	0.0020	0.0485	2.60	0.7918	0.2032	0.0013	0.0000
10	18.50	23.50	6.80	7.41	0.0220	0.0150	18.40	5.10	0.1530	0.0070	0.0370	2.70	0.7996	0.2004	0.0030	0.0000
20	20.80	27.60	7.43	9.50	0.0043	0.0008	18.40	9.20	0.0290	0.0010	0.0036	2.60	0.7598	0.2402	0.0004	0.0000
30	23.00	29.00	7.26	9.95	0.0039	0.0000	16.40	12.60	0.0590	0.0010	0.0013	1.50	0.7438	0.2526	0.0004	0.0000
40	23.40	30.80	7.15	10.80	0.0010	0.0016	18.20	12.60	0.0090	0.0010	0.0008	1.50	0.7228	0.2637	0.0007	0.0124
50	23.40	32.00	7.10	10.05	0.0048	0.0017	19.00	13.00	0.0090	0.0010	0.0000	0.90	0.6877	0.2801	0.0025	0.0311
60	22.70	29.30	6.84	9.50	0.0024	0.0014	17.20	12.10	0.0090	0.0010	0.0009	0.50	0.6878	0.2735	0.0039	0.0382
70	20.30	32.40	6.65	0.90	0.0123	0.0000	19.50	12.90	0.0090	0.0010	0.0055	0.50	0.6900	0.2699	0.0046	0.0383
80	17.60	29.70	6.66	8.87	0.0239	0.0009	18.40	11.30	0.0040	0.0060	0.0029	2.60	0.7115	0.2582		0.0287
90	19.30	29.50	6.85	9.80	0.0000	0.0000	18.30	11.20	0.0190	0.0010	0.0044	4.44				

Table K-1. Continued.

NEW FORK LAKE MICROCOSM # 9

DAY	ALK	HARD	PH	DO	TP	OP	CA	MG	NO3	NO2	NH3	TOC	N2	O2	CO2	CH4
0	17.50	21.00	6.94	7.20	0.0315	0.0183	11.20	9.80	0.1000	0.0020	0.0485	2.60	0.7909	0.2073	0.0011	0.0000
10	18.00	22.40	6.60	7.44	0.0200	0.0170	19.40	3.00	0.1740	0.0060	0.0150	2.60	0.8000	0.2000	0.0030	0.0000
20	19.80	28.60	7.50	9.40	0.0080	0.0039	18.40	10.20	0.0180	0.0020	0.0012	1.60	0.7627	0.2373	0.0003	0.0000
30	21.50	27.10	7.32	10.05	0.0033	0.0000	17.40	9.70	0.0290	0.0010	0.0053	1.40	0.7463	0.2527	0.0004	0.0000
40	21.40	29.90	7.16	9.90	0.0010	0.0024	18.20	11.70	0.0090	0.0010	0.0024	1.60	0.7287	0.2645	0.0011	0.0057
50	23.40	34.00	6.70	6.75	0.0082	0.0025	18.00	16.00	0.0090	0.0010	0.0000	2.10	0.7518	0.2313	0.0074	0.0158
60	24.60	31.30	6.51	4.25	0.0113	0.0021	20.20	11.10	0.0490	0.0010	0.0009	2.60	0.8029	0.1694	0.0102	0.0273
70	22.70	31.40	6.43	3.30	0.0196	0.0100	19.50	11.90	0.0090	0.0010	0.0071	4.90	0.8473	0.1226	0.0116	0.0285
80	21.00	32.70	6.38	1.27	0.0228	0.0074	19.40	13.30	0.0090	0.0010	0.0028	4.70	0.9073	0.0803		0.0092
90	23.40	31.90	6.43	2.00	0.0010	0.0000	19.60	12.30	0.7490	0.0010	0.0000	5.83				

NEW FORK LAKE MICROCOSM # 10

DAY	ALK	HARD	PH	DO	TP	OP	CA	MG	NO3	NO2	NH3	TOC	N2	O2	CO2	CH4
0	17.90	20.70	7.01	7.20	0.0275	0.0147	14.60	6.10	0.1000	0.0020	0.0518	1.90	0.7905	0.2075	0.0011	0.0000
10	18.00	22.40	6.60	7.04	0.0200	0.0150	18.40	4.00	0.1530	0.0070	0.0620	2.40	0.8002	0.1998	0.0030	0.0000
20	20.80	29.60	6.61	6.80	0.0185	0.0092	18.40	11.20	0.1490	0.0010	0.0020	0.50	0.8157	0.1843	0.0048	0.0000
30	23.00	30.90	6.60	6.15	0.0170	0.0128	16.40	14.50	0.1890	0.0010	0.0005	1.20	0.8202	0.1787	0.0062	0.0000
40	23.80	33.80	6.49	5.40	0.0137	0.0103	20.20	13.60	0.1090	0.0010	0.0024	0.50	0.8386	0.1603	0.0072	0.0000
50	20.30	36.00	6.75	3.00	0.0111	0.0028	20.00	16.00	0.0090	0.0010	0.0018	2.70	0.8746	0.1165	0.0134	0.0078
60	21.30	36.40	6.27	1.00	0.0891	0.0194	21.20	15.20	0.0090	0.0010	0.0009	4.40	0.9291	0.0550	0.0159	0.0156
70	20.80	36.50	6.30	0.80	0.1535	0.1363	20.50	16.00	0.0790	0.0010	0.0410	2.80	0.9400	0.0356	0.0136	0.0223
80	23.80	34.70	6.48	0.44	0.2556	0.2277	19.40	15.30	0.0090	0.0010	0.0965	3.90	0.9325	0.0361		0.0296
90	23.90	34.70	6.44	0.40	0.2044	0.0443	20.10	14.60	0.0390	0.0010	0.0996	4.75				

Table K-1. Continued.

NEW FORK LAKE MICROCOSM # 11

DAY	ALK	HARD	PH	DO	TP	OP	CA	MG	NO3	NO2	NH3	TOC	N2	O2	CO2	CH4
0	17.90	20.70	7.01	7.20	0.0275	0.0147	14.60	6.10	0.1000	0.0020	0.0518	1.90	0.7892	0.2079	0.0010	0.0000
10	18.00	22.40	6.60	7.39	0.0210	0.0150	19.40	3.00	0.1540	0.0060	0.0400	2.30	0.7992	0.2008	0.0033	0.0000
20	20.80	28.60	6.61	6.90	0.0129	0.0089	18.40	10.20	0.1980	0.0020	0.0059	0.50	0.8163	0.1837	0.0049	0.0000
30	23.00	30.00	6.63	6.35	0.0158	0.0119	18.40	11.60	0.1990	0.0010	0.0045	1.20	0.8269	0.1720	0.0063	0.0000
40	22.90	29.90	6.57	5.30	0.0038	0.0045	20.20	9.70	0.0990	0.0010	0.0057	0.50	0.8410	0.1575	0.0069	0.0012
50	26.80	34.00	6.50	2.25	0.0129	0.0039	22.00	12.00	0.0090	0.0010	0.0000	2.10	0.8728	0.1136	0.0118	0.0086
60	25.10	37.40	6.31	0.70	0.1068	0.0255	20.20	17.20	0.0090	0.0010	0.0023	3.90	0.9118	0.0649	0.0135	0.0230
70	18.80	35.40	6.26	0.95	0.1462	0.1313	18.50	16.90	0.0190	0.0010	0.0217	4.20	0.9182	0.0411	0.0108	0.0381
80	23.30	34.70	6.42	1.03	0.1611	0.1529	18.40	16.30	0.0290	0.0010	0.0608	3.60	0.8938	0.0460		0.0474
90	23.70	34.60	6.44	1.15	0.1093	0.0013	19.90	14.70	0.0170	0.0030	0.0894	3.70				

NEW FORK LAKE MICROCOSM # 12

DAY	ALK	HARD	PH	DO	TP	OP	CA	MG	NO3	NO2	NH3	TOC	N2	O2	CO2	CH4
0	17.90	20.70	7.01	7.20	0.0275	0.0147	14.60	6.10	0.1000	0.0020	0.0518	1.90	0.7903	0.2077	0.0010	0.0000
10	18.00	22.40	6.70	7.34	0.0180	0.0150	18.40	4.00	0.1270	0.0130	0.0700	3.70	0.7981	0.2019	0.0027	0.0000
20	20.80	29.60	6.64	7.00	0.0160	0.0080	19.40	10.20	0.1980	0.0020	0.0004	0.50	0.8144	0.1856	0.0047	0.0000
30	23.00	30.00	6.73	6.45	0.0134	0.0113	17.40	12.60	0.2090	0.0010	0.0037	1.10	0.8263	0.1737	0.0061	0.0000
40	22.90	31.80	6.59	5.20	0.0038	0.0095	20.20	11.60	0.1140	0.0050	0.0049	0.50	0.8343	0.1650	0.0068	0.0000
50	23.90	32.00	6.50	4.30	0.0123	0.0034	20.00	12.00	0.0790	0.0010	0.0000	1.20	0.8697	0.1292	0.0123	0.0000
60	18.80	32.30	6.26	3.60	0.0019	0.0013	20.20	12.10	0.0590	0.0010	0.0031	0.50	0.8759	0.1231	0.0122	0.0000
70	19.30	34.40	6.28	2.80	0.0099	0.0050	22.60	11.80	0.0790	0.0010	0.0194	0.80	0.9178	0.0805	0.0111	0.0000
80	28.00	33.70	6.42	2.75	0.0050	0.0050	20.40	13.30	0.0790	0.0010	0.0358	2.80	0.9226	0.0766		0.0000
90	21.20	33.90	6.46	2.00	0.0020	0.0020	19.80	14.10	0.0880	0.0020	0.0333	3.44				

Table K-2. Chemical and gas composition data for Bear Lake microcosm experiments.

BEAR LAKE MICROCOSM # 1

DAY	ALK	HARD	PH	DO	TP	OP	CA	MG	NO3	NO2	NH3	TOC	N2	O2	CO2	CH4
0	245.4	254.0	8.45	7.10	0.0144	0.0119	117.0	137.0	0.1870	0.0030	0.0506	2.00	0.8071	0.1922	0.0018	0.0000
10	235.6	269.3	8.01	7.40	0.0192	0.0046	120.0	149.3	0.0860	0.0140	0.0159	1.00	0.8007	0.1987	0.0029	0.0000
20	266.1	281.0	8.02	7.45	0.0063	0.0003	133.0	148.0	0.0670	0.0030	0.0013	1.10	0.7907	0.2053	0.0025	0.0000
30	256.4	273.0	7.98	7.95	0.0085	0.0013	126.0	147.0	0.0470	0.0030	0.0047	2.60	0.7910	0.2067	0.0023	0.0000
40	264.0	266.0	8.08	7.04	0.0071	0.0000	121.0	145.0	0.0090	0.0010	0.0096	0.90	0.7912	0.2087	0.0021	0.0000
50	247.0	264.0	8.22	6.80	0.0070	0.0010	144.0	120.0	0.0090	0.0010	0.0090	4.20	0.7961	0.2031	0.0024	0.0000
60	250.0	268.0	7.92	5.60	0.0007	0.0000	148.0	120.0	0.0090	0.0010	0.0048	2.17	0.8271	0.1721	0.0029	0.0000
70	247.0	256.0	8.00	5.00	0.0360	0.0020	140.0	116.0	0.0190	0.0010	0.0070	2.60	0.8451	0.1536	0.0031	0.0000
80	255.0	260.0	7.87	4.20	0.0030	0.0000	138.0	122.0	0.0490	0.0010	0.0000	4.10	0.8707	0.1279	0.0047	0.0000
90	243.0	268.0	7.82	4.40	0.0110	0.0050	148.0	120.0	0.0990	0.0010	0.0170	4.80	0.8778	0.1209	0.0046	0.0000

BEAR LAKE MICROCOSM # 2

DAY	ALK	HARD	PH	DO	TP	OP	CA	MG	NO3	NO2	NH3	TOC	N2	O2	CO2	CH4
0	242.5	260.0	8.48	7.50	0.0138	0.0082	121.0	139.0	0.0840	0.0060	0.0590	0.90	0.8096	0.1895	0.0018	0.0000
10	247.5	261.4	8.09	7.30	0.0067	0.0043	112.0	149.4	0.0860	0.0140	0.0116	2.20	0.8027	0.1973	0.0029	0.0000
20	269.5	273.0	8.18	7.70	0.0058	0.0000	136.0	137.0	0.0390	0.0010	0.0044	1.50	0.7864	0.2116	0.0020	0.0000
30	256.4	269.0	8.06	7.85	0.0073	0.0025	132.0	137.0	0.0290	0.0010	0.0041	3.00	0.7823	0.2120	0.0020	0.0000
40	260.0	259.0	8.17	7.42	0.0041	0.0020	134.0	125.0	0.0190	0.0010	0.0280	1.20	0.7807	0.2192	0.0020	0.0000
50	244.0	272.0	8.31	7.70	0.0040	0.0020	120.0	152.0	0.0090	0.0010	0.0000	6.50	0.7781	0.2211	0.0017	0.0000
60	254.0	260.0	8.13	7.50	0.0002	0.0006	147.0	113.0	0.0090	0.0010	0.0003	3.10	0.7857	0.2136	0.0029	0.0000
70	254.0	256.0	8.23	7.50	0.0440	0.0060	150.0	106.0	0.0880	0.0020	0.0100	2.10	0.7875	0.2108	0.0018	0.0000
80	240.0	252.0	8.16	8.00	0.0010	0.0000	128.0	124.0	0.0390	0.0010	0.0000	3.00	0.7896	0.2088	0.0022	0.0000
90	245.0	262.0	8.25	8.15	0.0130	0.0030	130.0	132.0	0.0190	0.0010	0.0120	2.20	0.7863	0.2122	0.0022	0.0000

Table K-2. Continued.

BEAR LAKE MICROCOSM # 3

DAY	ALK	HARD	PH	DO	TP	OP	CA	MG	NO3	NO2	NH3	TOC	N2	O2	CO2	CH4
0	246.9	256.0	8.46	7.20	0.0150	0.0136	120.0	136.0	0.0860	0.0040	0.0521	1.50	0.6091	0.1902	0.0018	0.0000
10	245.5	273.3	8.06	7.20	0.0096	0.0037	112.0	161.3	0.0880	0.0120	0.0083	3.50	0.6027	0.1971	0.0029	0.0000
20	266.1	269.0	8.17	7.90	0.0058	0.0003	133.0	136.0	0.0090	0.0010	0.0000	1.10	0.7905	0.2086	0.0021	0.0000
30	258.0	267.0	8.06	7.75	0.0097	0.0025	128.0	139.0	0.0190	0.0010	0.0041	3.30	0.7810	0.2160	0.0020	0.0000
40	256.0	270.0	8.17	7.61	0.0065	0.0000	138.0	132.0	0.0890	0.0010	0.0110	1.40	0.7805	0.2195	0.0019	0.0000
50	241.0	264.0	8.28	6.70	0.0070	0.0010	110.0	154.0	0.0090	0.0010	0.0000	2.40	0.7848	0.2147	0.0020	0.0000
60	255.0	264.0	8.03	5.80	0.0022	0.0000	123.0	141.0	0.0090	0.0010	0.0016	2.67	0.8151	0.1841	0.0028	0.0000
70	252.0	254.0	8.03	5.10	0.0220	0.0030	134.0	120.0	0.0290	0.0010	0.0080	4.00	0.6335	0.1649	0.0031	0.0000
80	257.0	254.0	7.89	3.70	0.0040	0.0000	128.0	126.0	0.0590	0.0010	0.0000	5.50	0.6711	0.1252	0.0053	0.0000
90	252.0	262.0	7.98	3.20	0.0170	0.0030	152.0	110.0	0.0990	0.0010	0.0050	5.70	0.8925	0.1063	0.0052	0.0000

BEAR LAKE MICROCOSM # 4

DAY	ALK	HARD	PH	DO	TP	OP	CA	MG	NO3	NO2	NH3	TOC	N2	O2	CO2	CH4
0	242.0	254.0	8.49	7.30	0.0138	0.0098	117.0	137.0	0.0850	0.0050	0.0559	1.20	0.6089	0.1903	0.0018	0.0000
10	240.5	257.4	8.05	7.20	0.0067	0.0043	108.0	149.3	0.0400	0.0200	0.0101	2.20	0.6031	0.1992	0.0029	0.0000
20	256.0	265.0	8.10	7.50	0.0046	0.0003	120.0	145.0	0.0090	0.0010	0.0005	1.80	0.7885	0.2103	0.0021	0.0000
30	256.0	267.0	8.01	7.80	0.0067	0.0025	134.0	133.0	0.0090	0.0010	0.0088	3.10	0.7874	0.2130	0.0023	0.0000
40	262.0	258.0	8.08	7.08	0.0071	0.0010	176.0	82.0	0.0090	0.0010	0.0160	1.40	0.7852	0.2148	0.0024	0.0000
50	249.0	292.0	8.23	6.60	0.0070	0.0010	136.0	156.0	0.0090	0.0010	0.0060	3.00	0.7941	0.2052	0.0019	0.0000
60	262.0	256.0	7.98	5.40	0.0022	0.0001	130.0	126.0	0.0090	0.0010	0.0022	3.02	0.8229	0.1762	0.0029	0.0000
70	258.0	261.0	7.98	4.80	0.0210	0.0030	132.0	129.0	0.0490	0.0010	0.0130	3.80	0.8464	0.1521	0.0034	0.0000
80	259.0	265.0	7.92	3.90	0.0060	0.0000	128.0	137.0	0.0290	0.0010	0.0010	4.20	0.8642	0.1342	0.0047	0.0000
90	256.0	270.0	7.99	4.10	0.0160	0.0030	162.0	108.0	0.0490	0.0010	0.0120	4.70	0.8721	0.1264	0.0045	0.0000

Table K-2. Continued.

BEAR LAKE MICROCOSM # 5

DAY	ALK	HARD	PH	DO	TP	OP	CA	MG	NO3	NO2	NH3	TOC	N2	O2	CO2	CH4
0	241.0	254.0	8.48	7.86	0.0157	0.0079	121.0	133.0	0.0760	0.0040	0.0628	1.50	0.6087	0.1905	0.0017	0.0000
10	247.5	261.4	8.06	7.30	0.0067	0.0031	116.0	145.5	0.0310	0.0110	0.0110	1.90	0.6002	0.1990	0.0027	0.0000
20	263.9	269.0	8.13	8.10	0.0069	0.0003	124.0	145.0	0.0090	0.0010	0.0013	1.30	0.7902	0.2094	0.0019	0.0000
30	256.0	261.0	8.02	7.90	0.0062	0.0013	120.0	141.0	0.0380	0.0020	0.0064	4.00	0.7826	0.2201	0.0018	0.0000
40	258.0	256.0	8.22	7.86	0.0053	0.0010	154.0	102.0	0.0090	0.0010	0.0096	2.70	0.7726	0.2274	0.0018	0.0000
50	242.0	268.0	8.26	6.60	0.0080	0.0020	142.0	126.0	0.0090	0.0010	0.0060	3.10	0.7787	0.2166	0.0020	0.0000
60	257.0	274.0	7.98	5.40	0.0017	0.0000	123.0	151.0	0.0090	0.0010	0.0028	3.30	0.8172	0.1824	0.0028	0.0000
70	258.0	259.0	8.00	4.90	0.0150	0.0030	128.0	131.0	0.0290	0.0010	0.0070	4.10	0.8327	0.1660	0.0030	0.0000
80	259.0	259.0	7.93	3.90	0.0060	0.0000	124.0	135.0	0.0390	0.0010	0.0000	4.60	0.8570	0.1416	0.0045	0.0000
90	252.0	270.0	7.91	2.90	0.0130	0.0030	126.0	144.0	0.0030	0.0010	0.0100	5.90	0.8919	0.1067	0.0055	0.0000

BEAR LAKE MICROCOSM # 6

DAY	ALK	HARD	PH	DO	TP	OP	CA	MG	NO3	NO2	NH3	TOC	N2	O2	CO2	CH4
0	243.9	262.0	8.44	7.30	0.0150	0.0064	152.0	110.0	0.0830	0.0070	0.0598	1.40	0.6091	0.1897	0.0017	0.0000
10	249.5	257.4	6.04	7.10	0.0096	0.0034	124.0	133.4	0.0510	0.0190	0.0143	1.60	0.6020	0.1974	0.0024	0.0000
20	269.5	269.0	8.10	7.40	0.0052	0.0008	120.0	149.0	0.0070	0.0030	0.0044	1.30	0.7988	0.2005	0.0022	0.0000
30	258.0	269.0	8.03	7.50	0.0050	0.0000	123.0	146.0	0.2290	0.0010	0.0056	4.10	0.7899	0.2101	0.0022	0.0000
40	260.0	262.0	8.19	7.33	0.0077	0.0010	173.0	89.0	0.0590	0.0010	0.0088	2.00	0.7858	0.2142	0.0022	0.0000
50	241.0	272.0	8.45	8.10	0.0060	0.0020	126.0	146.0	0.0090	0.0010	0.0000	1.80	0.7761	0.2233	0.0013	0.0000
60	254.0	256.0	8.26	8.50	0.0007	0.0000	104.0	152.0	0.0190	0.0010	0.0016	1.55	0.7678	0.2315	0.0011	0.0000
70	241.0	242.0	8.23	9.10	0.0400	0.0040	130.0	112.0	0.0290	0.0010	0.0030	1.90	0.7592	0.2391	0.0011	0.0000
80	238.0	236.0	8.24	9.70	0.0020	0.0000	114.0	122.0	0.0390	0.0010	0.0000	2.30	0.7565	0.2418	0.0015	0.0000
90	235.0	246.0	8.25	9.50	0.0080	0.0030	124.0	124.0	0.0390	0.0010	0.0080	2.70	0.7554	0.2431	0.0017	0.0000

Table K-2. Continued.

BEAR LAKE MICROCOSM # 7

DAY	ALK	HARD	PH	DO	TP	OP	CA	MG	NO3	NO2	NH3	TOC	N2	O2	CO2	CH4
0	243.0	254.0	8.45	7.30	0.0150	0.0095	133.0	121.0	0.0840	0.0060	0.0598	0.70	0.8112	0.1885	0.0016	0.0000
10	251.5	257.4	8.07	7.10	0.0096	0.0031	124.0	133.4	0.0300	0.0100	0.0083	2.70	0.7984	0.2013	0.0024	0.0000
20	269.5	257.0	8.16	8.40	0.0052	0.0000	128.0	129.0	0.0190	0.0010	0.0067	1.70	0.7898	0.2101	0.0018	0.0000
30	249.0	269.0	7.86	7.80	0.0073	0.0013	128.0	141.0	0.0190	0.0010	0.0056	2.50	0.7810	0.2150	0.0019	0.0000
40	264.0	257.0	8.22	7.61	0.0053	0.0010	148.0	109.0	0.0390	0.0010	0.0190	3.90	0.7775	0.2225	0.0020	0.0000
50	244.0	276.0	8.45	8.50	0.0040	0.0010	118.0	158.0	0.0090	0.0010	0.0050	2.40	0.7765	0.2227	0.0013	0.0000
60	248.0	254.0	8.20	8.50	0.0007	0.0000	107.0	147.0	0.0190	0.0010	0.0041	1.51	0.7740	0.2253	0.0013	0.0000
70	243.0	247.0	8.37	8.80	0.0090	0.0030	127.0	120.0	0.0290	0.0010	0.0050	2.10	0.7612	0.2371	0.0011	0.0000
80	238.0	244.0	8.32	9.70	0.0040	0.0000	117.0	127.0	0.0490	0.0010	0.0000	3.10	0.7585	0.2415	0.0013	0.0000
90	231.0	238.0	8.38	9.80	0.0110	0.0030	112.0	126.0	0.0290	0.0010	0.0080	2.50	0.7434	0.2550	0.0013	0.0000

BEAR LAKE MICROCOSM # 8

DAY	ALK	HARD	PH	DO	TP	OP	CA	MG	NO3	NO2	NH3	TOC	N2	O2	CO2	CH4
0	243.0	254.0	8.45	7.50	0.0116	0.0120	120.0	134.0	0.0840	0.0060	0.0651	1.60	0.8093	0.1900	0.0017	0.0000
10	253.5	265.3	8.07	7.10	0.0115	0.0028	116.0	149.3	0.0560	0.0140	0.0059	1.10	0.7988	0.2006	0.0024	0.0000
20	265.0	267.0	8.11	7.80	0.0150	0.0018	124.0	145.0	0.0380	0.0020	0.0021	1.80	0.7917	0.2083	0.0019	0.0000
30	258.0	269.0	8.07	7.75	0.0073	0.0013	120.0	149.0	0.0290	0.0010	0.0096	2.60	0.7811	0.2190	0.0019	0.0000
40	255.0	251.0	8.24	8.10	0.0053	0.0020	161.0	90.0	0.0490	0.0010	0.0140	3.10	0.7709	0.2291	0.0019	0.0000
50	242.0	268.0	8.38	7.50	0.0060	0.0020	122.0	146.0	0.0090	0.0010	0.0000	2.60	0.7722	0.2271	0.0021	0.0000
60	254.0	252.0	8.08	5.70	0.0027	0.0000	119.0	133.0	0.0790	0.0010	0.0009	2.75	0.7938	0.2056	0.0022	0.0000
70	252.0	262.0	8.08	6.40	0.0150	0.0030	130.0	132.0	0.0390	0.0020	0.0070	3.20	0.8092	0.1896	0.0024	0.0000
80	255.0	242.0	8.00	6.00	0.0040	0.0000	127.0	115.0	0.0490	0.0010	0.0000	4.30	0.8220	0.1766	0.0035	0.0000
90	249.0	264.0	8.07	5.80	0.0130	0.0030	128.0	136.0	0.0470	0.0030	0.0070	4.20	0.8316	0.1670	0.0045	0.0000

Table K-2. Continued.

BEAR LAKE MICROCOSM # 9

DAY	ALK	HARD	PH	DO	TP	OP	CA	MG	NO3	NO2	NH3	TOC	N2	O2	CO2	CH4
0	248.9	256.0	8.46	7.30	0.0125	0.0085	121.0	135.0	0.0750	0.0050	0.0766	1.10	0.8080	0.1912	0.0024	0.0000
10	253.5	265.3	8.07	7.00	0.0192	0.0031	124.0	141.3	0.0520	0.0180	0.0113	1.00	0.8011	0.1982	0.0028	0.0000
20	268.4	269.0	8.20	7.60	0.0075	0.0000	132.0	137.0	0.0190	0.0010	0.0028	2.20	0.7921	0.2071	0.0019	0.0000
30	258.0	277.0	8.05	7.60	0.0067	0.0007	128.0	149.0	0.0190	0.0010	0.0041	1.90	0.7890	0.2100	0.0019	0.0000
40	260.0	258.0	8.19	7.42	0.0077	0.0010	165.0	73.0	0.0290	0.0010	0.0100	3.80	0.7830	0.2170	0.0018	0.0000
50	248.0	268.0	8.35	6.30	0.0060	0.0010	108.0	160.0	0.0190	0.0010	0.0010	2.50	0.7891	0.2102	0.0024	0.0000
60	259.0	264.0	8.02	5.20	0.0022	0.0000	104.0	160.0	0.0690	0.0010	0.0048	3.09	0.8217	0.1775	0.0030	0.0000
70	258.0	269.0	8.04	4.90	0.0490	0.0030	124.0	145.0	0.0290	0.0010	0.0050	3.40	0.8366	0.1620	0.0030	0.0000
80	259.0	260.0	7.99	4.50	0.0050	0.0000	122.0	138.0	0.0590	0.0010	0.0000	4.40	0.8536	0.1449	0.0041	0.0000
90	254.0	268.0	7.99	3.80	0.0110	0.0020	127.0	141.0	0.0890	0.0010	0.0120	5.00	0.8711	0.1277	0.0047	0.0000

BEAR LAKE MICROCOSM # 10

DAY	ALK	HARD	PH	DO	TP	OP	CA	MG	NO3	NO2	NH3	TOC	N2	O2	CO2	CH4
0	243.9	260.0	8.46	7.30	0.0150	0.0079	122.0	138.0	0.0760	0.0040	0.0636	1.80	0.8117	0.1875	0.0017	0.0000
10	259.4	265.3	8.00	7.20	0.0077	0.0052	116.0	149.3	0.0360	0.0640	0.0196	1.20	0.8065	0.1904	0.0030	0.0000
20	271.7	273.0	7.96	6.70	0.0075	0.0049	116.0	157.0	0.1390	0.0010	0.0028	1.50	0.8139	0.1853	0.0030	0.0000
30	242.0	269.0	7.88	6.70	0.0100	0.0073	122.0	147.0	0.1290	0.0050	0.0120	2.30	0.8180	0.1805	0.0029	0.0000
40	260.0	264.0	7.94	6.02	0.0094	0.0100	179.0	85.0	0.1190	0.0010	0.0110	2.60	0.8213	0.1787	0.0029	0.0000
50	251.0	280.0	8.00	3.40	0.0080	0.0020	88.0	192.0	0.0090	0.0010	0.0010	3.90	0.8422	0.1594	0.0057	0.0000
60	264.0	270.0	7.75	1.90	0.0057	0.0009	120.0	155.0	0.0170	0.0030	0.0090	3.52	0.8978	0.1015	0.0062	0.0000
70	260.0	279.0	7.77	1.80	0.0240	0.0040	128.0	151.0	0.0190	0.0010	0.0150	3.90	0.9181	0.0805	0.0068	0.0000
80	263.0	263.0	7.72	1.40	0.0050	0.0000	125.0	138.0	0.0590	0.0010	0.0000	3.80	0.9246	0.0674	0.0073	0.0000
90	274.0	274.0	7.80	1.10	0.0110	0.0020	123.0	151.0	0.0570	0.0030	0.0110	3.70	0.9445	0.0542	0.0085	0.0000

Table K-2. Continued.

BEAR LAKE MICROCOSM # 11

DAY	ALK	HARD	PH	DO	TP	OP	CA	MG	NO3	NO2	NH3	TOC	N2	O2	CO2	CH4
0	249.8	262.0	8.48	7.40	0.0125	0.0086	120.0	142.0	0.0070	0.0030	0.0636	2.20	0.8091	0.1901	0.0017	0.0000
10	257.4	265.3	7.99	7.20	0.0144	0.0049	120.0	145.3	0.0350	0.0750	0.0340	1.50	0.8031	0.1912	0.0029	0.0000
20	270.6	285.0	7.92	6.70	0.0087	0.0055	120.0	165.0	0.1060	0.0740	0.0067	1.20	0.8105	0.1888	0.0031	0.0000
30	255.0	281.0	7.92	6.65	0.0097	0.0070	132.0	149.0	0.1430	0.0070	0.0088	2.60	0.8140	0.1840	0.0048	0.0000
40	262.0	266.0	7.90	6.17	0.0088	0.0088	168.0	98.0	0.1390	0.0010	0.0220	2.50	0.8203	0.1797	0.0061	0.0000
50	251.0	286.0	8.13	6.40	0.0120	0.0090	152.0	134.0	0.1490	0.0010	0.0010	1.60	0.8199	0.1793	0.0035	0.0000
60	259.0	268.0	7.97	6.00	0.0077	0.0073	148.0	120.0	0.1390	0.0010	0.0041	0.82	0.8301	0.1691	0.0030	0.0000
70	256.0	256.0	8.07	5.30	0.0300	0.0100	168.0	88.0	0.1390	0.0010	0.0080	1.20	0.8343	0.1643	0.0026	0.0000
80	255.0	273.0	7.93	6.30	0.0070	0.0060	127.0	146.0	0.1990	0.0010	0.0030	2.50	0.8345	0.1615	0.0035	0.0000
90	247.0	258.0	8.07	6.00	0.0160	0.0083	122.0	138.0	0.1040	0.0060	0.0070	1.40	0.8404	0.1583	0.0037	0.0000

BEAR LAKE MICROCOSM # 12

DAY	ALK	HARD	PH	DO	TP	OP	CA	MG	NO3	NO2	NH3	TOC	N2	O2	CO2	CH4
0	243.9	258.0	8.50	7.60	0.0207	0.0076	120.0	138.0	0.0880	0.0020	0.0575	1.40	0.6096	0.1896	0.0016	0.0000
10	259.4	257.4	8.01	7.20	0.0096	0.0055	116.0	141.4	0.0470	0.0630	0.0325	1.20	0.6077	0.1919	0.0029	0.0000
20	269.5	269.0	7.98	6.90	0.0098	0.0055	122.0	147.0	0.2460	0.0540	0.0021	1.10	0.8107	0.1885	0.0031	0.0000
30	242.0	277.0	7.52	6.90	0.0097	0.0076	124.0	153.0	0.1470	0.0030	0.0104	2.00	0.6164	0.1840	0.0052	0.0000
40	257.0	269.0	7.59	6.12	0.0100	0.0110	174.0	95.0	0.1390	0.0010	0.0310	2.40	0.8190	0.1810	0.0090	0.0000
50	244.0	274.0	7.83	4.00	0.0170	0.0020	132.0	142.0	0.0190	0.0030	0.0000	3.30	0.8343	0.1650	0.0084	0.0000
60	264.0	276.0	7.71	2.20	0.0037	0.0001	154.0	122.0	0.0029	0.0010	0.0035	3.57	0.6917	0.1067	0.0060	0.0000
70	258.0	262.0	7.72	1.60	0.0340	0.0040	132.0	130.0	0.0390	0.0010	0.0160	4.30	0.9261	0.0721	0.0078	0.0000
80	259.0	258.0	7.68	1.40	0.0050	0.0000	156.0	102.0	0.0790	0.0010	0.0030	5.30	0.9495	0.0485	0.0088	0.0000
90	254.0	268.0	7.81	1.10	0.0130	0.0020	154.0	114.0	0.0790	0.0010	0.0160	4.00	0.9536	0.0452	0.0094	0.0000

Table K-3. Temperature data for New Fork Lake microcosms.

DAY	BAR PRES	ROOM TEMP	INF TEMP	MICROCOSM EFFLUENT TEMPERATURE 1	2	3	4	5	6	7	8	9	10	11	12
2	643.9	19.4	18.0	19.4	19.4	19.4	19.4	19.4	19.4	19.4	19.4	19.4	18.2	18.2	18.2
4	642.9	19.6	19.6	19.3	19.5	19.6	19.5	19.6	19.6	19.3	19.6	19.5	18.6	18.6	18.6
6	642.2	18.9	18.0	19.4	19.4	19.4	19.4	19.4	19.4	19.4	19.4	19.4	18.2	18.2	18.2
8	641.0	18.9	19.0	19.2	19.6	19.6	19.6	19.5	19.4	19.4	19.6	19.5	18.2	18.2	18.2
10	642.5	18.6	18.0	19.4	19.4	19.4	19.4	19.4	19.4	19.4	19.4	19.4	18.2	18.2	18.2
12	644.5	18.8	18.0	19.4	19.4	19.4	19.4	19.4	19.4	19.4	19.4	19.4	18.2	18.2	18.2
14	642.7	18.7	18.0	19.4	19.4	19.4	19.4	19.4	19.4	19.4	19.4	19.4	18.2	18.2	18.2
16	643.1	18.8	18.0	19.4	19.4	19.4	19.4	19.4	19.4	19.4	19.4	19.4	18.2	18.2	18.2
18	641.0	18.6	18.0	19.4	19.4	19.4	19.4	19.4	19.4	19.4	19.4	19.4	18.2	18.2	18.2
20	644.1	18.7	18.0	19.4	19.4	19.4	19.4	19.4	19.4	19.4	19.4	19.4	18.2	18.2	18.2
22	647.5	18.8	18.0	19.4	19.4	19.4	19.4	19.4	19.4	19.4	19.4	19.4	18.2	18.2	18.2
24	644.2	18.8	18.0	19.4	19.4	19.4	19.4	19.4	19.4	19.4	19.4	19.4	18.2	18.2	18.2
26	646.3	18.6	18.0	19.4	19.4	19.4	19.4	19.4	19.4	19.4	19.4	19.4	18.2	18.2	18.2
28	641.6	18.6	18.0	19.4	19.4	19.4	19.4	19.4	19.4	19.4	19.4	19.4	18.2	18.2	18.2
30	646.2	18.6	18.0	19.4	19.4	19.4	19.4	19.4	19.4	19.4	19.4	19.4	18.2	18.2	18.2
32	644.9	18.6	18.0	19.4	19.4	19.4	19.4	19.4	19.4	19.4	19.4	19.4	18.2	18.2	18.2
34	644.7	18.7	18.0	19.4	19.4	19.4	19.4	19.4	19.4	19.4	19.4	19.4	18.2	18.2	18.2
36	643.5	18.8	18.0	19.4	19.4	19.4	19.4	19.4	19.4	19.4	19.4	19.4	18.2	18.2	18.2
38	643.2	18.6	18.0	19.4	19.4	19.4	19.4	19.4	19.4	19.4	19.4	19.4	18.2	18.2	18.2
40	644.3	18.8	18.0	19.4	19.4	19.4	19.4	19.4	19.4	19.4	19.4	19.4	18.2	18.2	18.2
42	644.1	18.8	18.0	19.4	19.4	19.4	19.4	19.4	19.4	19.4	19.4	19.4	18.2	18.2	18.2
44	641.4	18.9	18.0	19.4	19.4	19.4	19.4	19.4	19.4	19.4	19.4	19.4	18.2	18.2	18.2
46	642.6	18.9	18.0	19.4	19.4	19.4	19.4	19.4	19.4	19.4	19.4	19.4	18.2	18.2	18.2
48	639.8	22.0	18.0	19.4	19.4	19.4	19.4	19.4	19.4	19.4	19.4	19.4	18.2	18.2	18.2
50	639.7	22.7	18.6	22.8	22.8	23.4	23.2	23.1	23.1	23.4	23.2	23.0	21.4	21.2	21.0

Table K-3. Continued.

DAY	BAR PRES	ROOM TEMP	INF TEMP	MICROCOSM EFFLUENT TEMPERATURE 1	2	3	4	5	6	7	8	9	10	11	12
52	648.3	19.9	16.7	19.8	20.0	19.9	19.8	20.0	19.8	20.0	19.9	20.0	18.0	18.0	18.4
54	645.8	22.0	17.0	22.2	22.4	22.6	22.6	22.4	22.5	22.8	22.6	22.4	20.0	20.5	20.5
56	646.5	21.6	16.2	21.9	22.1	22.3	22.2	22.2	22.2	22.4	22.2	22.0	20.4	20.4	20.2
58	644.7	22.2	17.4	22.2	22.4	22.6	22.6	22.6	22.5	22.7	22.7	22.5	20.4	20.3	20.4
60	646.4	24.2	19.8	24.1	24.4	24.6	24.4	24.2	24.2	24.5	24.6	24.2	21.8	21.6	21.8
62	648.9	22.7	16.5	22.6	22.8	23.0	22.6	22.8	22.6	22.8	22.8	22.8	20.8	20.8	20.6
64	643.3	21.0	16.4	21.2	21.4	21.4	15.0	21.4	21.2	15.0	15.0	21.3	20.0	20.2	20.1
66	642.0	19.7	16.0	20.0	20.2	20.3	15.0	20.2	20.0	15.0	15.0	20.2	18.7	18.8	18.7
68	643.7	19.4	15.0	20.0	20.6	20.7	15.0	20.4	20.4	15.0	15.0	20.6	18.3	18.4	18.4
70	639.7	21.0	15.4	22.0	22.3	22.6	15.0	22.2	22.2	15.0	15.0	22.4	18.3	18.3	18.3
72	643.6	17.0	14.3	17.9	18.0	18.0	15.0	18.0	18.0	15.0	15.0	17.9	16.8	16.6	16.6
74	639.6	19.0	15.0	19.7	19.8	19.8	15.0	19.8	19.7	15.0	15.0	19.7	18.1	18.1	18.0
76	646.2	17.8	15.4	17.9	18.0	18.1	15.0	18.0	18.0	15.0	15.0	18.0	16.6	16.6	16.6
78	637.4	20.8	16.4	21.0	21.4	21.4	15.0	21.2	21.1	15.0	15.0	21.4	19.0	19.0	19.0
80	644.7	19.5	15.0	19.2	19.6	19.8	15.0	19.2	19.0	15.0	15.0	19.6	16.8	16.8	16.8
82	635.6	20.5	15.0	20.7	20.8	21.2	15.0	20.8	21.0	15.0	15.0	21.0	18.6	18.6	18.5
84	641.4	21.0	16.9	21.1	21.2	21.2	17.0	21.1	21.1	17.0	17.0	21.1	19.0	18.7	18.6
86	631.2	20.6	15.5	21.0	21.0	21.2	15.0	21.0	21.0	15.0	15.0	21.1	18.5	18.5	18.5
88	639.1	21.0	15.8	21.3	21.3	21.9	15.0	21.1	21.0	15.0	15.0	21.7	18.6	18.7	18.7
90	644.0	20.7	16.0	21.0	21.0	21.6	16.0	21.0	21.0	16.0	16.0	21.2	18.8	18.8	18.7

Table K-4. Temperature data for Bear Lake microcosms.

DAY	BAR PRES	ROOM TEMP	INF TEMP	MICROCOSM EFFLUENT TEMPERATURE 1	2	3	4	5	6	7	8	9	10	11	12
2	645.0	20.5	17.8	20.8	20.9	20.9	20.9	20.8	20.8	20.8	21.0	20.9	18.8	18.8	18.8
4	650.1	20.5	16.6	20.6	20.6	20.8	20.6	20.6	20.5	20.6	20.6	20.6	18.8	18.8	18.8
6	649.3	20.3	17.0	20.8	21.0	21.0	21.0	20.8	20.9	21.0	21.0	20.8	19.0	19.0	18.8
8	643.3	20.5	16.8	20.9	21.0	21.1	21.1	21.0	20.9	21.1	21.2	21.1	18.6	18.7	18.8
10	638.6	21.0	17.0	21.0	21.0	21.0	21.0	21.0	21.0	21.0	21.1	21.1	19.0	19.0	18.8
12	643.4	20.3	17.4	21.0	21.0	21.0	21.0	21.0	21.0	21.0	21.1	21.1	18.8	18.8	18.9
14	645.5	21.0	17.8	21.0	21.1	21.1	21.1	21.1	21.1	21.2	21.2	21.2	19.0	19.0	19.0
16	643.8	21.0	16.0	21.0	21.1	21.1	21.1	21.0	21.0	21.0	21.2	21.2	18.9	19.0	19.0
18	641.5	20.5	17.0	21.0	21.2	21.2	21.2	21.0	21.0	21.1	21.2	21.2	18.9	18.9	19.0
20	636.3	21.0	17.0	21.0	21.0	21.0	21.0	21.0	21.0	21.1	21.0	21.0	19.0	19.0	19.0
22	637.3	21.5	17.7	21.3	21.3	21.5	21.5	21.3	21.4	21.6	21.6	21.6	19.0	19.0	19.0
24	643.4	21.5	18.0	21.2	21.4	21.4	21.4	21.2	21.3	21.4	21.5	21.4	18.8	18.8	18.8
26	642.0	21.6	15.0	21.4	21.5	21.6	21.6	21.4	21.4	21.6	21.6	21.5	19.0	19.0	19.0
28	642.9	21.0	15.0	21.0	21.1	21.2	21.1	21.0	21.0	21.1	21.2	22.2	19.0	19.0	19.0
30	648.8	20.6	15.0	20.6	20.8	20.8	20.8	20.7	20.6	20.8	20.8	20.7	19.0	19.0	19.0
32	642.2	21.2	17.0	20.9	21.1	21.1	21.1	21.1	21.0	21.1	21.2	21.2	19.0	19.0	18.9
34	647.3	21.2	16.0	21.2	21.2	21.3	21.2	21.2	21.3	21.2	21.3	21.2	19.1	19.1	19.1
36	643.2	21.3	17.0	21.0	21.1	21.1	21.1	21.1	21.0	21.1	21.1	21.1	19.0	19.0	19.0
38	632.9	20.6	16.2	20.6	20.6	20.8	20.7	20.7	20.7	21.0	21.0	21.0	19.0	19.0	19.0
40	645.5	21.3	16.2	21.2	21.2	21.2	21.3	21.2	21.2	21.4	21.3	21.3	19.4	19.3	19.2
42	644.0	21.1	18.6	21.0	21.1	21.0	21.1	21.0	21.0	21.2	21.1	21.2	19.0	18.8	19.0
44	648.5	19.0	14.8	19.2	19.4	19.5	19.4	19.2	19.3	19.4	19.6	19.6	18.0	18.0	18.0
46	637.4	21.3	15.0	21.1	21.3	21.3	21.3	21.3	21.2	21.3	21.3	21.3	19.3	19.3	19.4
48	644.3	21.3	17.8	21.1	21.3	21.3	21.3	21.2	21.1	21.4	21.4	21.3	19.0	18.8	19.0
50	648.0	22.7	16.8	22.4	22.6	22.6	22.7	22.6	22.6	22.7	22.7	22.7	19.6	19.8	20.0

Table K-4. Continued.

DAY	BAR PRES	ROOM TEMP	INF TEMP	MICROCOSM EFFLUENT TEMPERATURE 1	2	3	4	5	6	7	8	9	10	11	12
52	638.8	22.3	19.0	22.0	22.2	22.2	22.3	22.2	22.0	22.3	22.3	22.2	19.8	19.8	19.8
54	640.1	22.4	17.8	22.0	22.2	22.3	22.3	22.2	22.4	22.4	22.5	22.5	20.0	19.8	19.8
56	632.4	21.8	16.0	22.0	22.1	22.2	22.2	22.0	22.1	22.2	22.4	22.2	20.0	20.0	20.0
58	625.9	22.0	16.5	22.0	22.1	22.2	22.2	22.1	22.1	22.2	21.3	21.1	19.8	19.8	19.9
60	639.3	23.0	18.0	22.5	22.6	22.8	23.0	23.0	22.8	23.0	23.0	23.0	20.0	20.0	20.0
62	631.3	22.4	19.0	22.6	22.6	22.8	22.7	22.7	22.6	22.7	22.8	22.8	21.8	21.8	21.8
64	653.3	22.4	18.0	22.2	22.5	22.6	22.6	22.5	22.6	22.7	22.7	22.7	20.0	20.0	20.0
66	653.4	22.4	19.0	22.2	22.3	22.4	22.4	22.4	22.3	22.4	22.4	22.4	19.8	19.8	19.8
68	639.5	22.5	18.0	22.2	22.4	22.6	22.5	22.5	22.6	22.4	22.6	22.5	19.9	19.8	19.8
70	645.5	22.0	17.4	22.2	22.4	22.3	22.4	22.4	22.4	22.4	22.4	22.4	20.0	19.8	20.0
72	641.7	22.1	17.5	22.0	22.2	22.2	22.3	22.2	22.2	22.3	22.4	22.4	19.7	19.7	19.8
74	637.8	22.8	17.3	22.4	22.6	22.6	22.8	22.8	22.6	22.6	22.7	22.6	20.0	20.0	20.0
76	635.5	22.2	16.0	22.2	22.4	22.6	22.6	22.5	22.4	22.6	22.6	22.5	20.0	19.7	19.7
78	629.5	22.2	21.2	22.4	22.2	22.4	22.4	22.4	22.4	22.5	22.4	22.5	19.9	19.8	19.7
80	643.9	22.0	17.0	22.0	22.2	22.2	22.1	22.1	22.2	22.2	22.2	22.2	19.4	19.5	19.5
82	648.7	22.8	16.0	22.5	22.6	22.8	22.6	22.8	22.6	22.8	22.6	22.6	19.9	19.8	19.8
84	642.9	22.5	16.0	22.8	22.6	22.8	22.8	22.8	22.8	22.9	22.9	22.8	20.0	20.0	20.2
86	642.1	22.5	15.0	22.5	22.5	22.6	22.7	22.8	22.8	22.8	22.8	22.8	19.8	19.8	19.8
88	644.1	22.4	17.4	22.4	22.6	22.7	22.6	22.6	22.7	22.8	22.8	22.7	20.0	19.9	19.8
90	644.8	22.0	16.0	22.0	22.3	22.4	22.4	22.3	22.3	22.5	22.5	22.4	20.0	20.0	20.0

Appendix L

Soluble Iron in NFL Microcosms

Table L-1. Soluble iron in NFL microcosms on day 77 of the experiment (Oct. 5, 1981).

Microcosm #	Light Conditions	Treatment	Iron Concentration (µg/l)
1	Diurnal	SLC	254
2	Diurnal	Unoiled	150
3	Diurnal	SLC	205
5	Diurnal	WC	414
6	Diurnal	Unoiled	<11
9	Diurnal	WC	245
10	Dark	SLC	3200
11	Dark	WC	2000
12	Dark	Unoiled	190